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FINAL REPORT

Regenerative Particulate Filter Development

MAY 1972

Prepared For

National Aeronautics and Space Administration
Manned Spacecraft Center
Houston, Texas

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Prepared by

MARTIN MARIETTA
DENVER DIVISION

NASA CR 115505

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REGENERATIVE PARTICULATE FILTER DEVELOPMENT

May 1972

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FOREWORD

This document presents the results of work performed by the Martin Marietta Corporation's Denver Division for the National Aeronautics and Space Administration, Manned Spacecraft Center. This final report was prepared as partial fulfillment of Contract NAS9-11984, Regenerative Particulate Filter Development. The NASA Technical Monitor was Mr. Albert F. Behrend, Jr. of the Crew Systems Division, Environmental Control and Life Support Systems Branch.

ABSTRACT

This report describes the effort accomplished under Contract NAS9-11984 to develop, design, and fabricate a prototype Filter Regeneration Unit used to regenerate (clean) fluid particulate filter elements. This report describes the development program that evolved a successful and highly efficient (98.7 to 100%) method of regenerating fluid filter elements using a backflush/jet impingement technique. Development tests were also conducted on a vortex particle separator designed for use in a zero-g environment. A "maintainable filter" was designed, fabricated and tested that allows filter element replacement without any leakage or spillage of system fluid. The report also describes spacecraft fluid system design and filter maintenance techniques with respect to inflight maintenance for the Space Shuttle and Space Station.

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DEFINITIONS AND SYMBOLS

Abbreviations

AC	AC Road Dust, AC Spark Plug, Division of General Motors Corporation
Dia	Diameter
EMER	Emergency
Hz	frequency, Hertz
OCS	Onboard Checkout System
N/A	Not Applicable
RH	Relative Humidity
VAC	Volts Alternating Current
VDC	Volts Direct Current
ΔP	Pressure drop
P	Pressure
T	Temperature
$\dot{w}$	Mass flow rate

British Units

amp	current, ampere
ft	length, feet
in	length, inches
GPM	flow rate, gallons per minute
psi	pressure, pounds per square inches
^oF	temperature, degrees Farenheit
#/hr	flow rate, pounds per hour

International Units

^oC	temperature, degrees centigrade
cm	length, centimeters
cm/sec	velocity, centimeters per second
gms	mass, grams
^oK	temperature, degrees kelvin
kg	mass, kilogram
kg/m^3	density, kilogram per cubic meter
kg/sec	flow rate, kilogram per second
m	length, meter
mg	mass, milligram
mm	length, millimeter
ml	volume, milliliter
m^3/sec	flow rate, cubic meters per second
N/m^2	pressure, newtons per square meter
$N \cdot s/m^2$	Dynamic viscosity, newton-second per square meter
μ	length, microns

I. SUMMARY AND RESULTS

A. INTRODUCTION

The objective of this contract was to develop, design, fabricate, and test prototype hardware that will be used to regenerate (clean) fluid particulate filters. The development of this item is applicable to the potable water, process water, thermal water, and the Freon-21 thermal systems for the Space Station, Space Shuttle, and the Space Station Prototype.

The current liquid filter designs for space application are not suitable for Space Shuttle/Station systems because of the extended use times required. The mission times of future space vehicles demand components having several orders of magnitude more life capability than present state-of-the-art offers. In addition, present Apollo inplace (nonreusable) fluid filters are not suitable for inflight maintenance and regeneration.

Since filter element replacement represents 20% or more of the scheduled maintenance on a fluid system, techniques must be employed whereby the elements can be changed out or regenerated in place. It is not practical to expect that, for every filter replacement, the system be drained, purged, filled and bled in addition to the replacement of filter elements. This contract has developed techniques and prototype hardware to provide a solution to both the regeneration and replacement of fluid filter elements.

B. TECHNIQUES AND HARDWARE

A backflush technique, using the same working fluid as the system, was found to be the most applicable filter cleaning process for spacecraft use in a zero-g environment. Other techniques were either difficult to adapt to a zero-g environment, would contaminate the spacecraft system (Freon, soap, etc.), would produce a hazard (acid bath), or were very complex (ultrasonics).

Hardware delivered on this contract included a special regenerative filter, a filter regeneration unit, a maintainable filter, and a demonstration test panel.

The filter regeneration unit (Figure I-1) is a portable self-contained unit that uses the backflush/jet impingement principle to regenerate fluid filters. Regeneration is accomplished with no loss of fluid. The process does not degrade the filter elements, and uses the same working fluid as the respective spacecraft subsystem. High cleaning efficiencies (98.7 to 100%) were obtained using the techniques developed during this program.

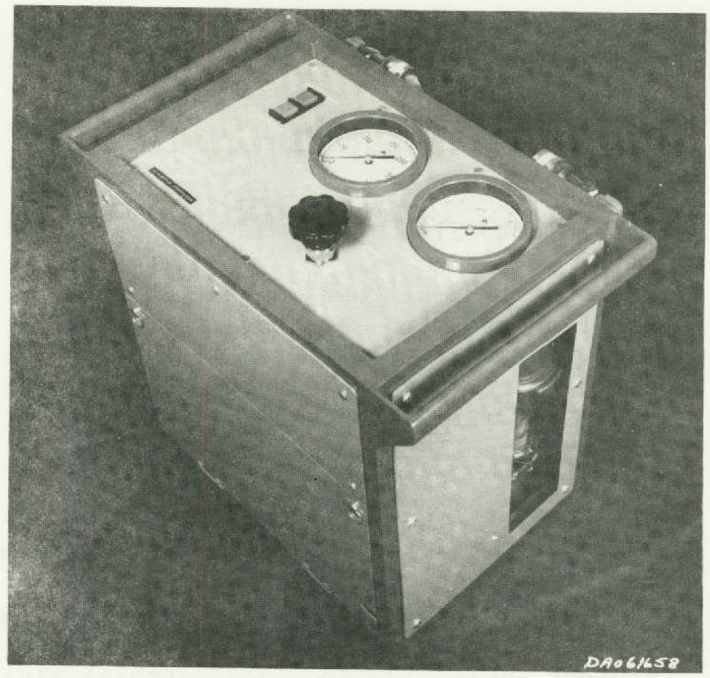

Figure I-1 Filter Regeneration Unit

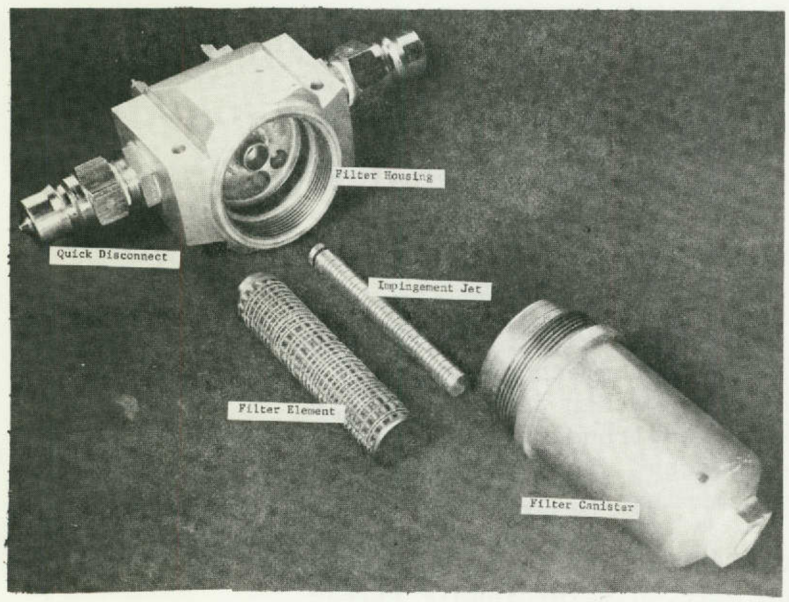

Figure I-2 Regenerative Filter

The regeneration process is simple in operation and requires a minimum of astronaut involvement. The backflush operation requires only that the regeneration unit be connected to the spacecraft regenerative filter through the inlet and outlet disconnects, and that the unit be turned on. The unit will automatically turn off at the end of the regeneration cycle.

The regenerative filter (Figure I-2) is of a special configuration that was designed and developed specifically for the backflush regeneration technique. It consists of a filter body, a backflush impingement "jet", a special filter element, and the inlet and outlet disconnects.

It was found that at a backflush flow rate of 6.31×10^{-4} m^3/sec (10 GPM) for five minutes, cleaning efficiencies of 98 to 100% were obtained. These high cleaning efficiencies were obtained by the use of a backflush/impingement jet that was designed and developed to improve the backflush efficiency. The jet principle involves the impingement of high velocity jets of fluid onto the inner surface of the filter element, Figure I-3, to loosen and remove filtered particulate. Several backflush-jet configurations were tested during the development program. The slotted jet shown in Figure I-2 was found to be the most efficient for the filter

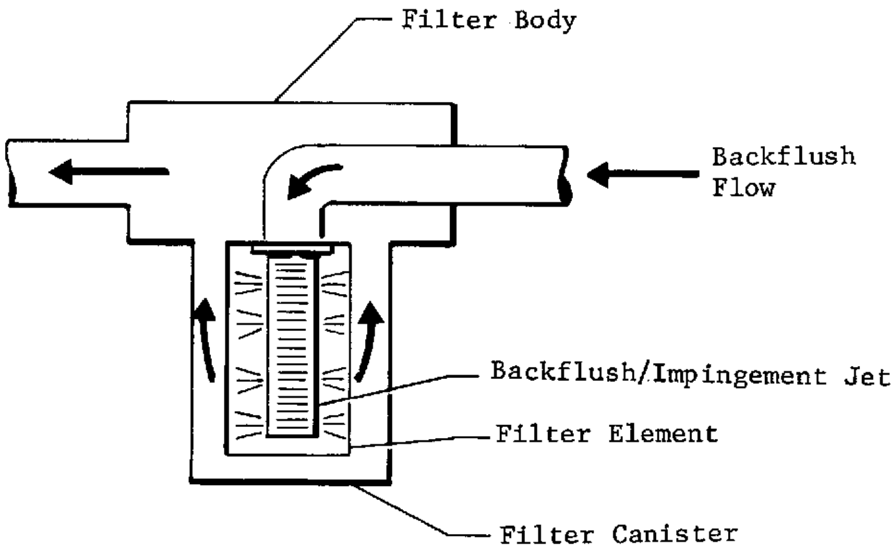

Figure I-3 Regenerative Filter Principle

elements tested during this program. This increase in velocity allowed the use of lower flow rates, and hence decreased power requirements, while maintaining a high cleaning efficiency. Industry contacts and a literature search revealed that the lowest flow rates previously used on the same sized filter was 18.39×10^{-4} m^3/sec (30 GPM), or three times as high as that developed on this program.

A Hydraulic Research filter element, Figure I-2, (10 micron nominal, 25 micron absolute) was used for most of the test program. The element is constructed from a stainless steel composite material with four different layers, consisting of: (1) coarse outside screen to prevent impingement of high velocity particles on the precision filter cloth, (2) a first-stage, fine-wire depth cloth which provides the main filtration, (3) a second-stage, woven-wire mesh for a backup filtration media and to provide absolute particle control, and (4) a coarse, inside screen to provide separation to the inside pleats and to keep open the exit flow path. The coarse inside screen also strengthens the pleats against high differential pressures in the normal direction. The elements tested in this program also had a special outer retaining spring to prevent deformation in the reverse direction during backflush.

The maintainable filter (Figure I-4) offers an alternative to filter element cleaning. It provides a solution to filter change-out for systems requiring quick turn-around (Shuttle), for fluids that involve safety in handling (propellants and bacteria-laden systems), for clean fluid systems whereby the introduction of bacteria cannot be tolerated (potable water), and for one-of-a-kind fluids where it may not be practical to supply an additional filter regeneration unit.

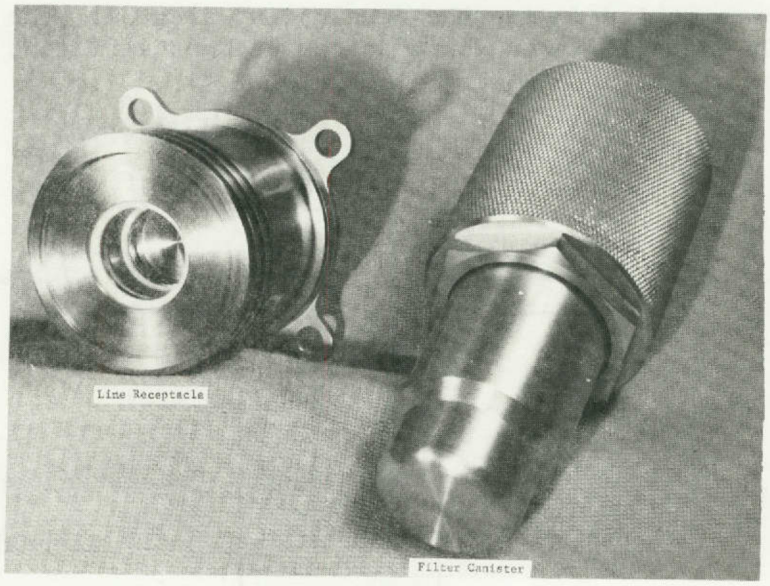

Figure I-4 Maintainable Filter

The maintainable filter is designed so that the filter canister and element can be quickly changed out with no leakage or spillage of fluid. The filter can be connected or disconnected simply by a hand-torque operation that does not require any tools. This type of design precludes draining a fluid system, purging, and fill and bleed operations.

The demonstration test panel (Figure I-5) provides the test interface for loading contaminants onto the regenerative filter, and also provides a mounting fixture for the regenerative and maintainable filters while testing.

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A schematic of the prototype filter regeneration unit, and a regenerative filter, is shown in Figure I-6.

The filter regeneration unit is a self-contained unit that connects to the regenerative filter with fluid connectors, forming a closed loop system. The unit contains its own pump and motor which provide the flow rate and pressure required for the backflush operation. Flow from the pump is directed in the reverse direction through the regenerative filter, where the particulate is washed from the filter element and carried to the vortex particle separator. Most of the particulate (93%) is separated out and collected in the particle separator trap.

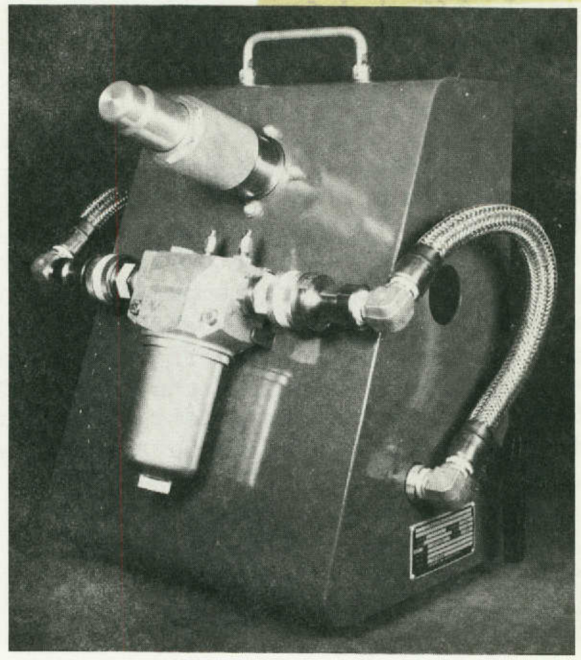

Figure I-5 Demonstration Test Panel

The remainder of the particulate passes out of the separator and is collected in the secondary filter. The secondary filter insures that no fine particles are transmitted to the downstream surface of the regenerative filter element where, upon system start-up, the particles would flow into the spacecraft system and cause a possible contamination failure of the system. The secondary filter can also be regenerated with the filter regeneration unit.

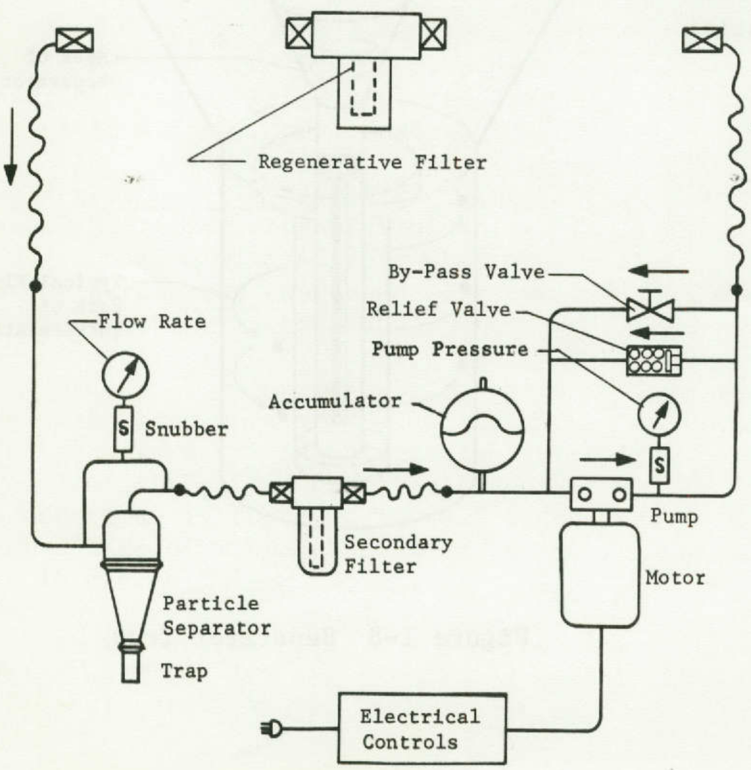

Figure I-6 Filter Regeneration Unit Schematic

The vortex particle separator is a key element in the filter regeneration unit. In the backflush cycle, the particles that are backflushed from the system regenerative filter are removed in the particle separator and collected in the separator trap, thus reducing the maintenance activity normally associated with filter change-out. The development tests conducted on this program proved that with the proper configuration, the separator could be used as a means of removing and collecting large amounts of contaminant. Efficiencies ranging from 88 to 93% were obtained using particles that ranged in size from 43 to 200 microns. The vortex particle separator is a passive component with no moving parts. The separator employs a vortex action where the particles are thrown to the outer surface of the separator and eventually are forced down to the trap where they are accumulated and prevented from re-entering the normal flow (see Figure I-7). Several different trap designs were tested, and the one shown in Figure I-8 proved to be the most efficient. The circular

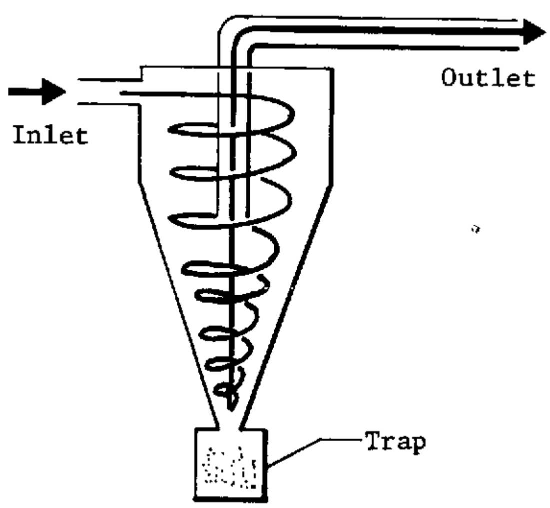

Figure I-7 Separator Principle

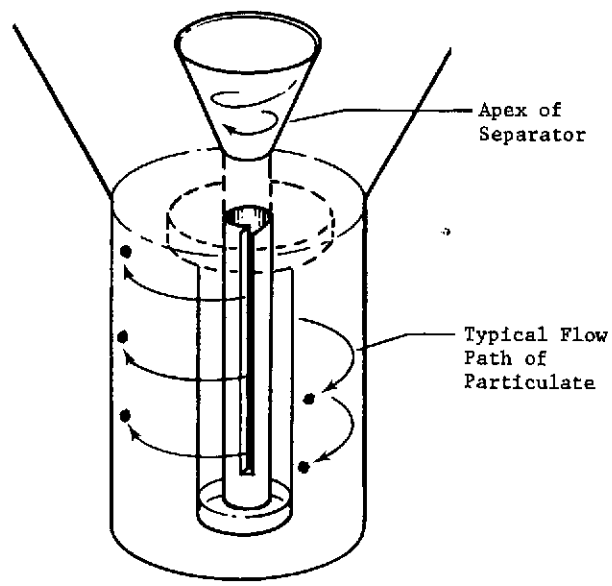

Figure I-8 Separator Trap

motion of the fluid entering the trap throws the suspended particles out through a tangential slot. When the flow stops, the particle trap prevents the particles from re-entering the separator when in a zero-g environment. The particle trap can be sized so that little or no change-out is required during a normal mission. With proper disconnect design, the trap can be removed without loss of water.

A systems analysis was conducted considering the potable water, process water, thermal water, and Freon-21 thermal systems for the Space Station, Space Shuttle, and Space Station Prototype. This study concluded that the process water system (which contains the shower, dish washer, and clothes washer) will contain the largest contamination load, and is therefore the prime candidate for filter element regeneration. The potable water and thermal water systems are much cleaner systems but, since all three represent the same fluid, they can also be included in the regeneration plan. It is recommended, however, that filter elements from the potable water system be regenerated and then used in the thermal water systems, or as a back-up to the secondary filter in the regeneration unit, to prevent the introduction of contamination into the potable water systems. The filter regeneration unit could also be used as a ground servicing unit for the Shuttle program.

The filters in the Freon-21 thermal system can be regenerated; however, another filter regeneration unit would be required because of the different working fluid. The maintainable filter would provide a good alternative for this system.

The maintainable filter could be used in any of the fluid systems, but is particularly attractive for systems requiring quick turnaround (Shuttle), and for clean (or relatively clean) systems such as the potable water, thermal water, and Freon-21 thermal systems. The maintainable filter design could be modified to allow cleaning, if required.

C. TESTING

Three categories of testing were conducted on this program; (1) development testing, (2) zero-g testing, and (3) performance testing.

1. Development Test Program - The development test program was concerned with the development of the backflush/jet impingement technique, the impingement jet, and the vortex particle separator. All of the development tests were conducted with water as the working fluid, and graded dust (AC coarse road dust) as the

contaminant. AC road dust was used because it is a known and graded contaminant, and thus decreases the error and variables incurred during testing. Previous tests conducted by Martin Marietta, have established the particle size, percent distribution, and number/size of particles per given weight of contaminant. The particle size range of AC coarse road dust varies between 0 and 200 microns, with a small percentage of the particles exceeding 200 microns. Tests conducted on the separator, and later on some of the backflush runs, were run with the AC road dust graded to 43 microns, which eliminated the majority of the particles below 43 microns.

Thirty backflush regeneration tests were conducted during the development program. Two different types of filter elements and four different impingement jets were tested at flow rates varying from 4.29 to 8.5 10^{-4} m^3/sec (6.8 to 13.5 GPM). Regeneration efficiencies of 98 to 100% were achieved at backflush flow rates of 6.31 x 10^{-4} m^3/sec (10 GPM). On one occasion during the test program, elements were ultrasonically cleaned in a solution of "Joy" detergent. It is significant to note that the tests following the cleaning did not indicate any better dirt capacity or additional level of cleanliness over that obtained by backflushing.

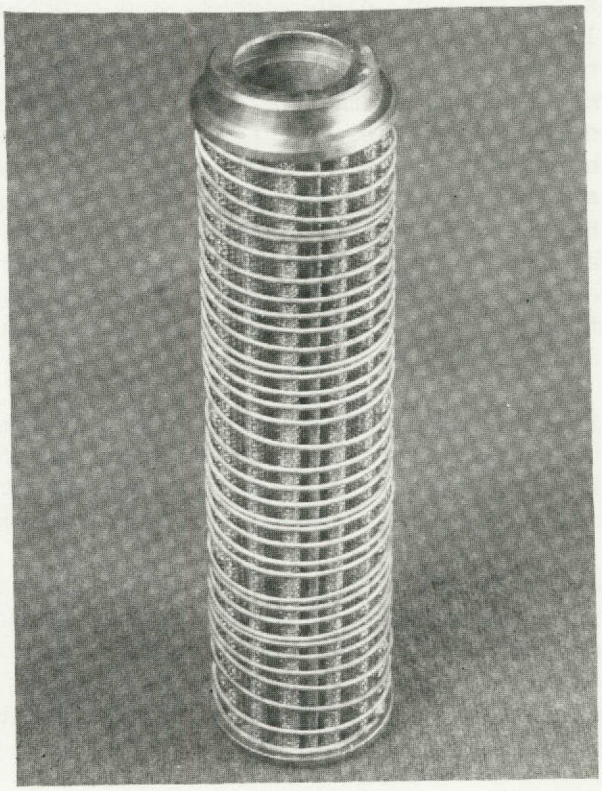

Figure I-9 10 Micron Filter Element

A filter element having a rating of 10 microns nominal - 25 microns absolute, was the selected filter element and is shown in Figure I-9. This fine filtration level is more stringent than that required by even the potable water system, and hence it is believed that the testing conducted under this program was more stringent than required.

The amount of contaminant that was retained on the filter element varied widely (Table I-1) and was a function of particle size. The theory is that the smaller particles clog the pores in the filter quicker, with less capability to retain the contaminant.

Effluent from a clothes washing machine (soapy water) completely clogs the filter in a matter of seconds, with a filter capacity of only 0.23 grams. When using AC coarse road dust, the filter would accept 1.0 grams of dust at a ΔP of 142 x 10^3 N/m^2 (20 psi) and, at the same pressure drop, the filter would accept 3.4 grams of AC road dust that was 43 microns and larger.

Table I-1 Filter Element Capacity

CONTAMINANT	SIZE RANGE microns	CAPACITY grams
Clothes Wash Water	Unknown	0.23
AC Road Dust	0 - 200	1.0
AC Road Dust	43 - 200	3.4

Twenty-nine development tests were conducted on the vortex particle separator, and separation efficiencies of 93% were achieved. During testing, it was found that the particle trap configuration had a large influence on separation efficiency. As much as 13% difference in efficiency was noted between models. An exit tube with one tangential slot was found to be the most efficient trap configuration.

2. Zero-G Tests - Preliminary zero-g tests of the particle trap were conducted on a KC-135 aircraft. These simulated tests showed that the slotted tangential trap was effective in retaining particles in a zero-g environment.

3. Performance Tests - Performance tests were conducted on the assembled filter regeneration unit. The first series of tests were conducted with AC road dust as the test contaminant, and the second series was conducted with the effluent contaminant from a clothes washing machine and a whole-body shower.

The results of the regeneration tests for the AC road dust and the wash water were very good, however, the filter that was loaded with shower water did not return to its original condition. Program limitations did not permit additional tests with shower water to determine if there was a real discrepancy, or if this test was just a case of mismatch between the shower water particle size and the 10 micron filter rating.

The results of the performance tests show that the filter regeneration unit and its components are capable of effectively regenerating filter elements. An overall unit efficiency of 96 percent was achieved in recovering the contaminants from a backflushed element, using a five-minute backflush cycle.

The results show that a filter element can be regenerated and return to the initial pressure drop versus flow characteristics. The results of nine regeneration cycles, using two different filter elements, are shown on Figure I-10. These results indicate that the filter elements are being regenerated to their initial condition, and that the backflush/jet impingement technique is a valid and efficient method for filter recycling.

D. RESULTS

The more pertinent results derived during this program are listed below.

1) Filter element regeneration efficiencies of 98.7 to 100% were achieved with a backflush flow cycle of five minutes at a flow rate of 6.31×10^{-4} m^3/sec (10 GPM) using water as the working fluid.

2) Particle separation efficiencies of 93% were achieved using a specially designed vortex particle separator.

3) The operation of the particle separator trap was successfully tested and verified in a zero-g environment.

4) The overall efficiency of the filter regeneration unit, as determined by actual tests, was 96%.

5) A maintainable filter has been designed, fabricated, and tested that allows replacement of filter elements with no leakage or spillage, and does not require that the system be shut down, drained, or purged.

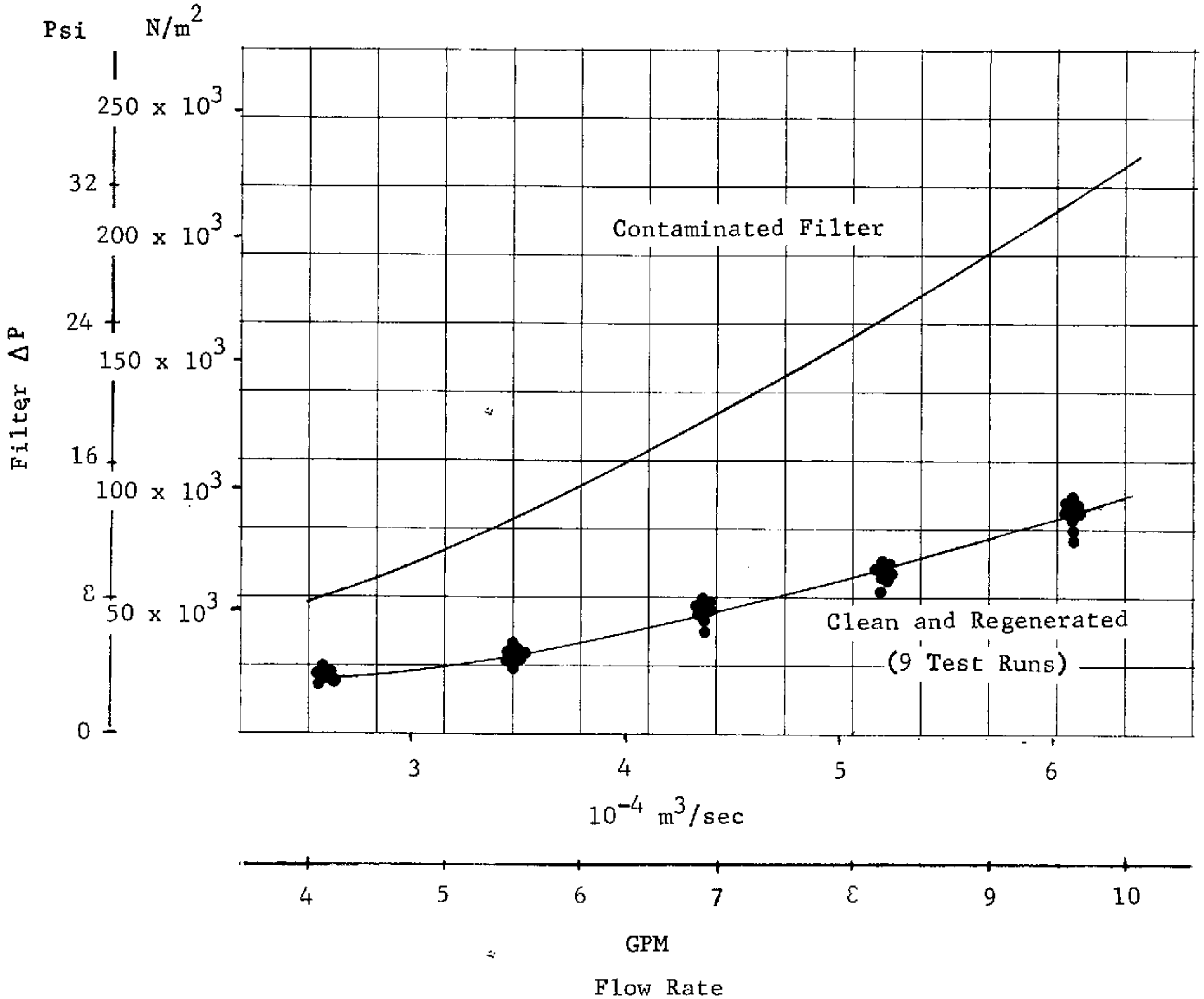

Figure I-10 Filter Regeneration Performance

II. CONCLUSIONS AND RECOMMENDATIONS

A. CONCLUSIONS

1) The development tests on this contract have proven that the backflush/jet impingement technique is a feasible means of cleaning a fluid system filter.

2) Filter regeneration can be accomplished with little or no loss of system fluids, and the accumulated contaminants can be collected in a zero-g environment.

3) The filter regeneration unit can be used for all of the Space Station and Space Shuttle water and Freon-21 systems, and is particularly suited for systems with high contamination loads such as the process water system.

4) The maintainable filter can be used in any of the water and Freon-21 systems, but provides better use in the Shuttle Orbiter fluid systems and the potable water, thermal water, and Freon-21 thermal systems.

B. RECOMMENDATIONS

In the performance of a contract in an area of new technology, such as filter regeneration and inflight maintenance, it is incumbent upon the participants to identify those areas of technology that require future development. In addition, this contract requires that recommendations be provided for additional areas of investigation based on the results of the contractual effort. The formulation of programs, such as Space Shuttle, Space Station, and other future manned missions, depends upon the proper development of future technology so that a solution to problems is developed on a timeline consistent with its needs.

Space maintenance and filter regeneration is of prime importance to the fulfillment of the long-duration mission, and requires proper development to meet those future requirements. Six specific areas of future technology follow, and it is recommended that further effort be continued in these areas.

1. Flight Prototype - Filter Regeneration Unit - This contract has demonstrated the feasibility of a regenerative filter system using a backflush/jet impingement technique. The hardware produced under this contract was of a prototype nature, and therefore was not designed as a flight-weight system. A logical continuation of this development would be to design, build, and test a flight-weight regenerative system having the features of low pressure drop, maintainability, compact design, fluid/environment compatibility, and also compatibility with the Space Shuttle/Station interfaces.

2. Flight Prototype - Maintainable Filter - The maintainable filter delivered under this contract was designed for a low-flow-rate, 1/4-inch system. The testing performed on this filter has demonstrated that the basic design is solid, and that a maintainable filter can be built that has the characteristics of minimum leakage and spillage. Since this filter was designed and fabricated, several design improvements have been realized that would improve the pressure drop characteristics and reduce the total weight. It is recommended that the basic design be updated to meet the requirements of a Space Shuttle fluid system that has a higher flow rate. The design should reflect minimum pressure drop and flight weight along with minimal or no leakage and spillage. A flight prototype should be fabricated and extensively tested in the environment that it would experience on the Space Shuttle.

3. Light Solids Collection - On future missions, the life support systems will contain whole body showers, clothes washing machines and dish washing machines. The water systems will also necessarily be regenerative in that the water will be reused. In the described water systems, the light solids (hair, skin particles, lint, food particles) pose a serious problem to filters in that they form a matte on the surface of the filter and quickly clog it -- stopping the system flow. A method must be developed whereby the light solids can be collected without incurring the disadvantages inherent to filters. The method should be positive in operation, compatible with a zero-g environment, and require little or no maintenance. It is recommended that a development program be initiated to derive concepts for light solids collection, and to perform development tests to arrive at a feasible solution.

4. Maintainable Components - During the performance of this contract, it again became apparent that existing component designs do not have provisions for inflight maintenance. Solutions are required for: (1) system isolation so that components can be removed from the system when they fail, (2) a disconnect design that has minimum pressure drop, minimum spillage, reduced envelope

size, and increased reliability, and (3) a solution for solving fluid-system leaks in a zero-g environment. In these areas, there are no existing components or methods that fulfill the requirement. Future long-duration missions will require, as a minimum, inflight maintenance and the ability to isolate, repair and remove components from a system. Technology and developed hardware are lagging in this field and require additional emphasis.

5. Analytical Analysis of Process Water - Analytical data is not available on the particle composition of shower water or the effluent from clothes washers and dish washers. Some chemical analysis has been obtained but the number of particles and their size range, the weight of contaminant generated per operation and its composition are not available. This data is basic to the design of process water systems, and particularly to filter sizing. Filter size (area) is dependent upon the total flow through the element, and the size and type of contaminant. The micron rating of the filter is also dependent upon the size of particles to be expected. For example, commercial detergents will immediately clog a 10-micron filter. Regeneration frequency, and an estimate of scheduled maintenance activity, is also dependent on filter size and contaminant loading. Development tests should be conducted to arrive at the above data. In addition, the tests should evaluate filter micron size, clogging, and the contaminants contained in different types of soaps and detergents.

6. Regeneration of Bacteria Filters - Bacteria filters are used throughout the water systems in a spacecraft. These filters are constructed from nonmetallic materials, and presently are "throw-away" elements. If these filter elements were constructed from a material that would structurally withstand a regeneration process, and if these very fine micron filters could be regenerated, a large savings in resupply weight could be saved which would result in a total cost savings to a long-duration mission. It is recommended that a program be initiated to determine the feasibility of bacteria filter-element regeneration.

III. FILTER REGENERATION SYSTEM

A. PROGRAM DESCRIPTION

The Regenerative Particulate Filter Development program was performed within an 11-month period, with 8-1/2 months devoted to technical effort. The objective of this program was to develop a method for regenerating fluid particulate filters; and to design, fabricate and test a prototype filter regeneration unit. The development of the filter regeneration system is applicable to the Space Shuttle and Space Station programs. The fluid subsystems to be considered for the baseline were the potable water, process water, thermal water, and Freon-21 thermal systems. Four major prototype hardware items were delivered on this program; (1) a Filter Regeneration Unit, (2) a Regenerative Filter, (3) a Demonstration Test Panel, and (4) a Maintainable Filter.

The program was performed in the following six tasks:

Task I: Preliminary Design, Analysis, and Development Testing

Task II: Prototype Design

Task III: Prototype Fabrication

Task IV: Performance Testing

Task V: Hardware Delivery

Task VI: Documentation and Final Presentation

1. Task I: Preliminary Design, Analysis, and Development Testing - The initial step in the program was to review the requirements for each fluid system on the Space Station, Space Shuttle, and the Space Station Prototype; and to establish a detailed program baseline. The evolving Space Shuttle/Station requirements were carefully tracked throughout the program to ensure that the results of the program were current and applicable.

During Task I a study was conducted to determine the merits and deficiencies of each regeneration technique that is presently state-of-the-art, and to arrive at the best approach for use in a zero-g spacecraft environment.

A systems configuration study was conducted to determine the best method of incorporating a backflush regeneration technique into a spacecraft systems design. Considerations in this study were fixed, installed, and portable regeneration units with various options of redundant filters, bypass loops, pumps, etc. The results of this study are presented in Section D of this chapter.

Preliminary concept design analyses were conducted during Task I to determine the vortex particle separator sizing and pressure drop, system pressure drops, flow rates, impingement velocities, and pump sizing.

All the development testing on the regeneration techniques and particle separation were also performed during this task. In addition, zero-g tests were conducted on the KC-135 aircraft to test the performance of the zero-g particle trap in a zero-g environment.

A design review was conducted at the conclusion of Task I to review concepts and to select the best concept for design of the filter regeneration unit.

2. Task II: Prototype Design - The detailed design for the filter regeneration unit and the demonstration test panel were completed during this task. Selection and procurement of hardware were also initiated. The basic design philosophy for the prototype unit was to use commercial components whenever possible to conserve costs. A design review was conducted at the end of this task and prior to fabrication.

3. Task III: Prototype Fabrication - All of the necessary fabrication and assembly was completed under this task. Verification tests and calibration of hardware were also performed during this period.

4. Task IV: Performance Testing - The purpose of task IV was to conduct those tests necessary to evaluate the performance of the filter regeneration unit, and to gain operating data, prior to delivery of the unit to NASA. These tests included leak checks, proof pressure, flow calibration, filter pressure drop, contaminant buildup, and operating procedure checkout. Tests were conducted on subassemblies within the unit to determine regeneration and particle separation efficiencies.

Final performance tests were conducted on the filter regeneration unit as a total assembly using filters that were contaminated with AC road dust, effluent from a clothes washing machine, and effluent from a whole body shower. Pre-delivery and confirmation tests were also conducted on the unit prior to shipment.

5. Task V: Hardware Delivery - All of the hardware that was produced under this program was shipped to NASA-MSC and demonstrated. Major items of deliverable hardware were the Filter Regeneration Unit, Regenerative Filter, Demonstration Test Panel, and the Maintainable Filter.

6. Task VI: Documentation and Final Presentation - Seventeen documentation submittals were made on this program. The major documentation items included a program plan, a test plan, monthly progress reports, and a final report. A final presentation was conducted at NASA-MSC at the conclusion of the program.

B. CONSTRAINTS AND GUIDELINES

To provide the proper design and development of the Regenerative Particulate Filter System for the Space Shuttle/Station, a complete knowledge and understanding of the applicable fluid systems is required. This includes characteristics such as system flow rates, media, pressure, temperature, particulate size and constituents, particulate generation rates and power supplies. These characteristics are discussed in the following and were utilized as constraints and guidelines throughout the design and development activities.

The fluid systems that were considered were the potable water system, process water system, thermal water system and the Freon-21 thermal system for the Space Shuttle, Space Station, and Space Station Prototype (SSP) as applicable. Tables III-1 and III-2 give the design parameters for these systems where Table III-1 provides the flow rates and Table III-2 gives flow rates as well as temperatures and pressures. There is a considerable variation in flow rates between different fluid systems and also between the same systems on different vehicles. For design and testing purposes of this contract the following parameters were established as the baseline fluid system.

$$\text{Flow Rate} = 4.29 \times 10^{-4}\ m^3/sec\ (6.79\ GPM)$$

$$\text{Working Pressure} = 550 \times 10^3\ N/m^2\ (80\ psi)$$

$$\text{Temperature} = 278 \text{ to } 344^{o}K\ (40\text{-}160^{o}F)$$

This flow rate was selected for a number of reasons. It is greater than 14 of the 18 flow rates indicated and therefore covers approximately 80% of all the systems listed. The selected flow rate is from the heat exchanger water loop on the Space Station Prototype which is one of the more firmly defined systems. The Space Station Prototype

Table III-1 Subsystem Fluid Flow Rates
$m^3/sec \times 10^{-4}$, (GPM)

Subsystem	Space Station		Space Station Prototype (SSP)	Shuttle Orbiter	
	McDonnell Douglas Martin Marietta	North American		McDonnell Douglas Martin Marietta	North American
Thermal Subsystem					
Water Cabin Loop	1.04 (1.65)	3.19 (5.05)	8.8 (13.9)	0.42 (0.7)	1.03 (1.63)
Water Heating Loop	1.04 (1.65)	N/A	N/A	N/A	N/A
Heat Exchanger Water Loop	N/A	N/A	4.29 (6.79)	N/A	N/A
Freon 21 Radiator Loop	1.62 (2.56)	9.44 (14.9)	15.05 (23.8)	2.94 (4.65)	2.46 (3.9)
Freon 21 Power Boom Loop	N/A	5.15 (8.15)	N/A	N/A	N/A
Water Management Subsystem					
Potable Water Subsystem	---	0.0112 (0.0178)	0.00177 (0.0028)	---	---
Wash Water Collection Subsystem	0.304 (0.48)	0.0208 (0.033)	0.354 (0.56)	N/A	N/A

NOTES:

(1) Flow rates in parenthesis ( ) are in gallons per minute, GPM.

(2) N/A - Not Applicable

Table III-2 Subsystem Fluid Parameters

Subsystem	Space Station: McDonnell Douglas Martin Marietta	Space Station: North American	Space Station Prototype (SSP)	Shuttle Orbiter: McDonnell Douglas Martin Marietta	Shuttle Orbiter: North American
Thermal Subsystem					
Water Cabin Loop	two circuits $\dot{w}$ = 0.103 kg/sec ea (825 lb/hr) ΔP = 330 x 10^3 N/m^2 (48 psi) T = 1.11 to 5.56 ^oC (34 to 42^oF)	$\dot{w}$ = 0.318 kg/sec (2521 lb/hr) T = 4.44 to 65.6^oC (40 to 150 ^oF)	$\dot{w}$ = 0.875 kg/sec (6950 lb/hr) ΔP = 206 x 10^3 to 550 x 10^3 N/m^2 T = 13.89 to 16.11^oC (57 to 61 ^oF)	$\dot{w}$ = 0.0498 kg/sec (395 lb/hr) ΔP = 275 x 10^3 N/m^2 (40 psi) T = 1.11 to 23.89 ^oC (34 to 75^oF)	$\dot{w}$ = 0.103 kg/sec (815 lb/hr) Interchanger T = 7.22^oC (45^oF)
Water Heating Loop	two circuits $\dot{w}$ = 0.103 kg/sec (825 lb/hr) ΔP = 165 x 10^3 N/m^2 (24 psi) T_{max} = 132.2^oC (270^oF)	N/A	N/A	N/A	N/A
Water Heat Exchanger Loop	N/A	N/A	$\dot{w}$ = 0.426 kg/sec (3395 lb/hr) ΔP = 206 x 10^3 to 550 x 10^3 (30-80 psi) T = 4.44 to 19.44^oC (40 to 67^oF)	N/A	N/A

Table III-2 Subsystem Fluid Parameters (continued)

Subsystem	Space Station		Space Station Prototype (SSP)	Shuttle Orbiter	
	McDonnell Douglas	North American		McDonnell Douglas	North American
Freon 21 Radiator Loop	8 circuits $\dot{w}$ = 0.228 kg/sec ea (1815 lb/hr) T = 1.11 to 5.56 °C (34 to 42°F)	$\dot{w}$ = 1.30 kg/sec (10,300 lb/hr) @ 7.22°C (45°F) T = -1.11 to -7.22 to 32.2°C (30-45 to 90°F)	$\dot{w}$ = 2.13 kg/sec (16,900 lb/hr) ΔP = 206 x 10^3 to 412 x 10^3 N/m^2 (30 to 60 psi) T = 2.22 to 14.44°C (36 to 58°F)	$\dot{w}$ = 0.415 kg/sec (3290 lb/hr) ΔP = 412 x 10^3 N/m^2 (60 psi) T = 1.11 to 43.89 °C (34 to 111°F)	$\dot{w}$ = 0.348 kg/sec (2760 lb/hr) Interchanger T = 4.44°C (40°F)
Freon 21 Power Boom Loop	N/A	$\dot{w}$ = 0.745 kg/sec (5,900 lb/hr) @ -6.67°C (20°F) T_{op} = -1.11 to 71.11°C (30-160°F) $T_{non\ op}$ = -53.8 °C (-65°F)	N/A	N/A	N/A
Water Management Subsystem					
Potable Water Subsystem	-----	$\dot{w}$ = 0.00112 kg/sec (8.9 lb/hr) continuous	$\dot{w}$ = 0.000177 kg/sec (1.4 lb/hr) nom. $\dot{w}$ = 0.00755 kg/sec (60 lb/hr) flush	-----	-----
Wash Water Collection Subsystem	$\dot{w}_{max}$ = 0.0302 kg/sec (240 lb/hr) for 10 min, $\dot{w}$ = 0.00248 kg/sec (19.7 lb/hr) for 18 hr.	$\dot{w}$ = 0.00208 kg/sec (16.5 lb/hr) for 18 hr/day operation	$\dot{w}$ = 0.0353 kg/sec (280 lb/hr nominal T = 15.56 to 71.11°C (60 to 160°F)	N/A	N/A

Notes: (1) N/A - Not Applicable

system will be one of the first to have hardware fabricated and also the first to conduct an extended performance test. As a comparison to the overall list of flow rates, the median of those from Table III-1 is between 1.04×10^{-4} and 1.62×10^{-4} m^3/sec (1.65 and 2.56 GPM) and the average flow rate is 3.15×10^{-4} m^3/sec (5.00 GPM). It must also be realized that some of these flow rates are relatively constant over a period of time (water coolant) and some vary considerably over a period of time (process water).

The working pressures for the systems listed ranged from 165×10^3 to 550×10^3 N/m^2 (24 to 80 psi). A working pressure of 550×10^3 N/m^2 (80 psi) was chosen as the baseline because it is the maximum system pressure and does not present any problems to the design of the regeneration unit.

The temperature range of 278 to 344°K (40 to 160°F) was selected because it included the low end of the coolant loops as well as the sterilization temperatures on the high end. The fluid system temperature does not present a major constraint on the filter regeneration unit design as does the flow rate, but must be considered with respect to seals and materials.

The four fluid systems considered each have their own characteristics regarding particulate generation, size, and constituents. Systems such as the Freon-21 and water coolant systems, which are closed loop, will have a relatively low rate of particulate generation. For closed loop systems such as these the highest particulate generation rate is during the initial start-up period when contaminant that is induced during fabrication and assembly is washed through the system. The only other sources of contaminants are those that are generated through normal wear of the system components. The potable water system is a clean system with low particulate generation due to the required cleanliness of the stored water, and the small number of particulate sources in the system such as valves, seals, etc. The process water system, on the other hand, will have a relatively high rate of contaminant generation as well as large size particulates such as skin, body hair, and food wastes. The other system contaminants consist of small particulates such as microorganisms, inorganic and organic salts and soluble materials (see Table III-3).

The current cleanliness control specifications for the four systems discussed are shown on Table III-4. The allowable quantities of particulate are given as a function of size ranges. This specification provides the filter requirements of the system as well

Table III-3 Typical Fluid Composition Encountered in Various Space Station Systems

Material	Potable Water	Shower/Wash Water	Cooling Water	Process Water	Freon-21 Coolant
SOLUBLES					
Calcium		X	X	X	
Chloride		X	X	X	
Chromium	X	X	X	X	
Copper	X	X	X	X	
Iron	X	X	X	X	
Magnesium		X	X	X	
Manganese	X	X	X	X	
Nickel	X	X	X	X	
Potassium		X	X	X	
Silver	X	X	X	X	
Sodium		X	X	X	
Zinc	X	X	X	X	
Amino Acids		X			
Cretinine		X			
Glucose		X			
Lactic Acid		X			
Urea		X			
Uric Acid		X			
Detergent		X		X	
Germicide				X	
NON-SOLUBLES					
Sebum		X			
Body hair, skin, etc.		X		X	
Clothing lint		X		X	
Food wastes				X	
Metallic fragments	X	X	X	X	X
Seal fragments	X	X	X	X	X
MICROORGANISMS					
Bacteria	X	X	X	X	X
Fungi	X	X	X	X	X
Protozoa	X	X	X	X	X

X - Designates presence of compound

Table III-4 Allowable Particle Size for Space Station Fluid Systems

Fluid	Max. Size per 500 Ml. Fluid	Particulate Particles, Number
(1) Potable Water	0-10 Microns	Unlimited
	10-25 Microns	875
	25-50 Microns	100
	50-100 Microns	50
	>100 Microns	2
(2) Process, Cooling Water	0-50 Microns	Unlimited
	50-75 Microns	100
	75-100 Microns	10
	>100 Microns	0
(3) Freon-21	0-50 Microns	Unlimited
	50-100 Microns	50
	100-250 Microns	4
	>250 Microns	0

as the assembly cleanliness level during fabrication. For the process water, the cooling water, and the Freon-21 systems a filter rated at 50 to 75 microns absolute will provide the necessary filtration to meet the particulate specifications. The potable water system will require a 10 to 25 micron absolute rated filter to meet the specifications shown. For development testing of the regenerative particulate filter it was decided to use a filter element rated at 10 microns nominal and 25 microns absolute which is the most restrictive rating of all the systems.

The cabin environment that the regenerative particulate filter system will operate in is within the normal human living ranges of pressure (1 atmosphere), temperature, 294°K (70°F), and humidity (40-60% RH). These do not impose any serious constraints but the zero-gravity environment of space does. This has to be considered even in the design of the development system because the fluid dynamics are directly affected by the zero-gravity environment. Other environments such as launch vibration and acceleration were not a requirement for the development of the prototype system. The structural integrity of the system is such that it could be designed to withstand normal launch environments without any anticipated problems.

The electrical power supply on the Space Station is anticipated to be 25,000 watts with miscellaneous power sources of 28 volt DC and 200 volt AC at 400 Hz. With the many systems that require electrical power, the power profile will vary over a period of time. In some cases where a large amount of power is required, it may have to be scheduled for use. On the other hand, with lower power requirements, the usage is not constrained. To date the power profile is not fully defined, but as a guideline, the regenerative particulate filter system should be designed for minimum power usage.

C. FILTER REGENERATION UNIT DESIGN

The filter regeneration unit, along with the regenerative filter, provide a system that utilizes a backflush/jet impingement concept to clean and recondition fluid system filters. This system simplifies the maintainability of fluid system filters. The system that was designed and fabricated on this contract demonstrates the feasibility of the backflush concept. The system is shown schematically in Figure III-1, and the following gives the detail description and operation of the overall system and components.

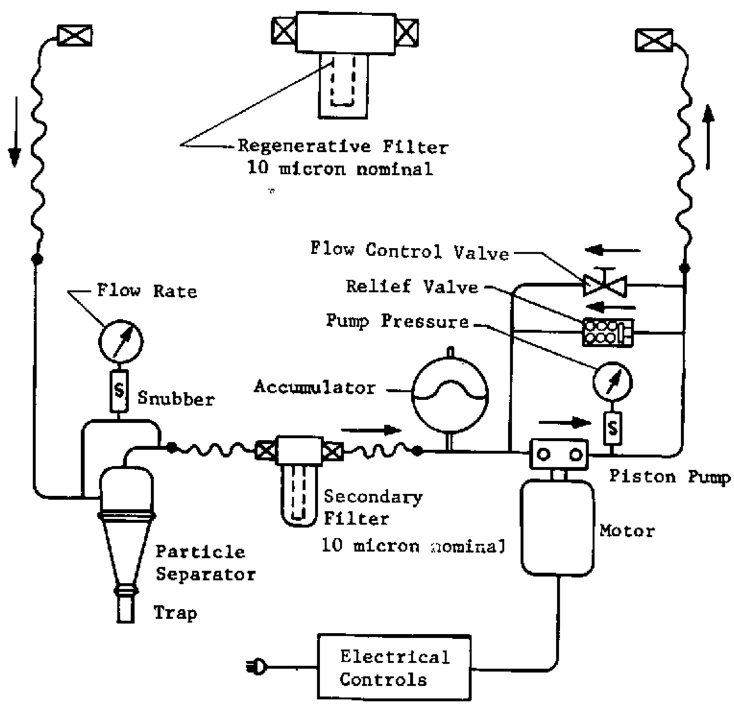

Figure III-1 Filter Regeneration Unit Schematic

1. Regenerative Filter - The regenerative filter consists of a filter body, a filter element, an impingement jet, and two quick disconnect nipples (see Figure III-2). The filter element is specially designed for backflushing and continuous reuse, and is sized for a flow rate of 4.29×10^{-4} m^3/sec (6.8 GPM). The element is rated at 10 microns nominal and 25 microns absolute. The filter element is constructed of stainless steel materials for extended life and ease of cleaning. The pleated composite material (Figure III-3) consists of (1) a coarse outside stainless steel screen which prevents impingement of high velocity particles on the precision filter cloth, as well as facilitating use of the total inlet filter surface, (2) a first stage fine wire depth cloth consisting of fine stainless steel fibers in a random but controlled matrix which provides the main filtration with a high dirt holding capacity and high particle removal efficiency, (3) a second stage woven stainless steel wire mesh which provides a backup filtration media as well as a uniform pore size to ensure absolute particle control, (4) a coarse inside stainless steel screen to provide separation to the inside of the pleats and additional strength for long life. The filter element also contains an outer stainless steel retaining spring which prevents deformation when backflushing.

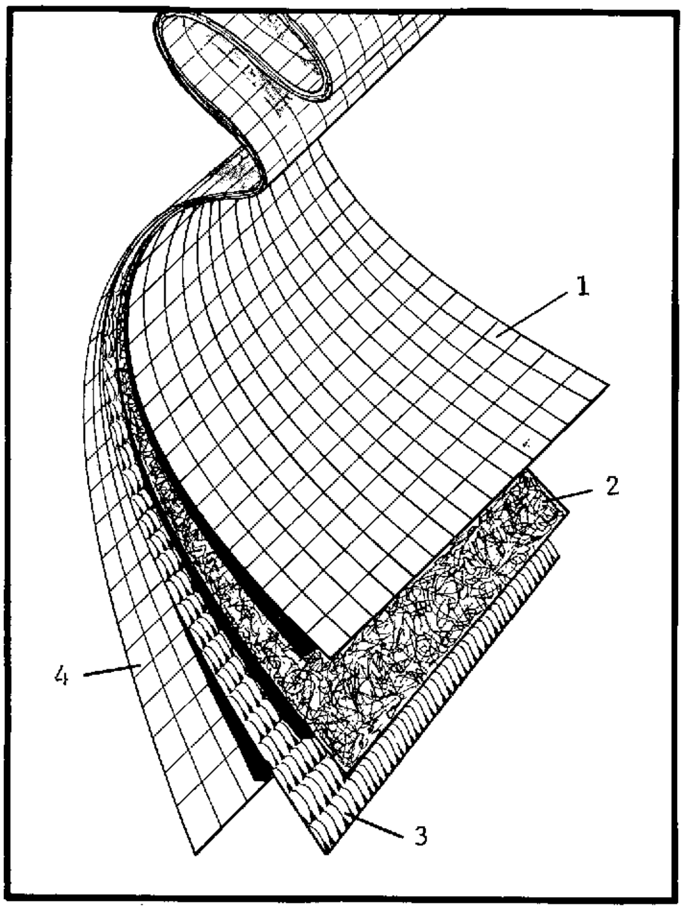

Figure III-3 Filter Element Material

Located within the filter element inside diameter is a special backflush impingement jet which adds very little pressure drop to the filter in the normal flow direction but improves the cleaning of the filter element during the backflush operation. During the backflush operation the impingement jet directs small high velocity jets of fluid onto the inner surface of the filter element

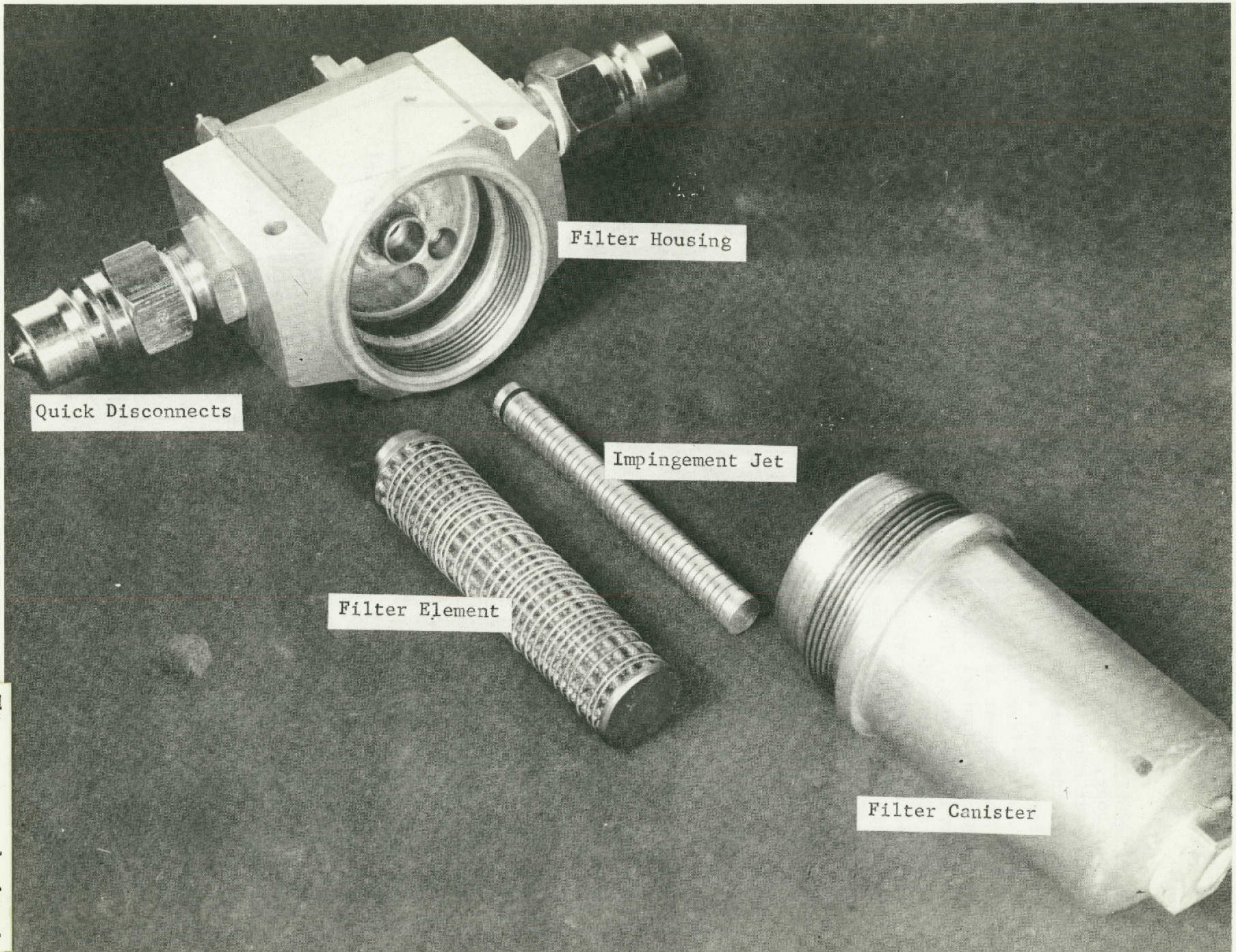

Figure III-2 Regenerative Filter Assembly facilitating particle removal and the overall backflush efficiency. The use of the impingement jet reduces the required backflush flow rate as well as the pump and motor size.

2. Filter Regeneration Unit - The filter regeneration unit is a self-contained unit that is fully automatic. All that is required is that a regenerative filter be attached to the unit by the flex hoses and quick disconnects provided. The "START CYCLE" button is then pushed to operate the unit for a set period of five minutes. The unit will shut off automatically and the regenerative filter is cleaned and ready for use.

The regenerative filter must be fully charged with fluid prior to connecting it to the regeneration unit to avoid induction of air into the backflush system. The inclusion of too much air will create pump noise and reduce operating efficiency. The mating halves of the quick disconnects must be attached to the same color coded halves to ensure proper orientation of the regenerative filter. Yellow has been designated as the color for the upstream port for backflush and downstream port for normal flow. The white color code is the opposite. If the filter is installed improperly there will be no personnel or equipment hazards but the system will not function as it was designed for, and regeneration will not take place.

During the five-minute cycle, the backflush flow through the regenerative filter removes the particles and carries them into the vortex particle separator (see Figure III-4) where 88% to 93% of the particles are removed from the fluid and retained in the separator trap. The remaining particles flow out of the separator and into the secondary filter where all remaining particles, 10 microns or larger, are filtered out of the fluid. The "cleaned" fluid continues on through the pump and back into the regenerative filter closing the backflush flow loop. This backflush action continues for five minutes, which has been determined to give the best overall efficiency with respect to cleaning and power requirements.

The control panel located on the top surface of the filter regeneration unit contains two switches, two gages, and one control valve (see Figure III-5). The switches are for starting the backflush cycle and for turning the unit off, if desired, before the backflush cycle is complete. If the "EMER STOP" button is used, the timer immediately resets to a full cycle such that when the "START CYCLE" is again depressed, a full five-minute cycle will commence. The "PUMP PRESSURE" gage shows the system pressure at the outlet port of the pump when the unit is operating and the residual pressure on the unit when it is not operating. The "BACKFLUSH FLOW"

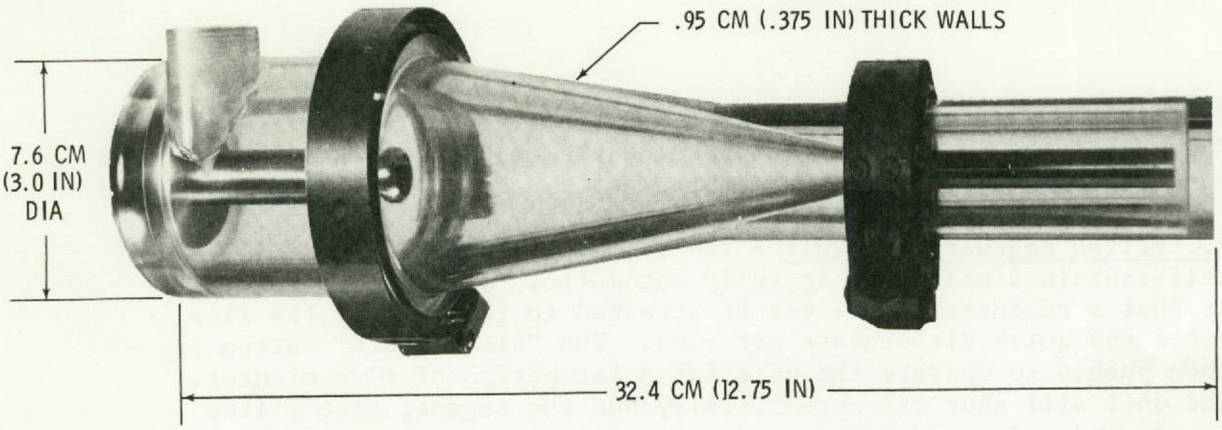

Figure III-4 Vortex Particle Separator

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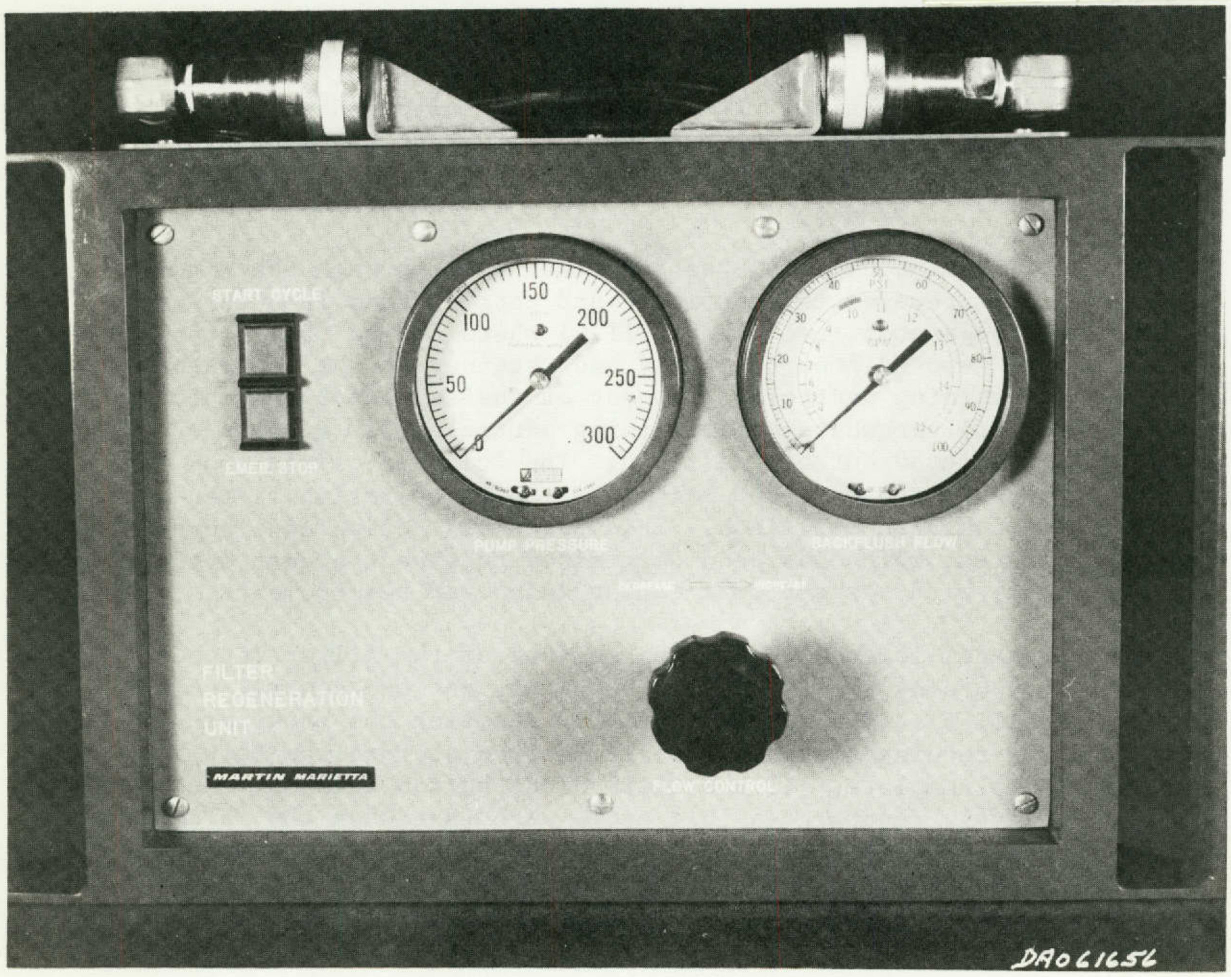

Figure III-5 Filter Regeneration Unit - Control Panel gage shows the flow rate, in GPM, through the regenerative filter as well as the differential pressure across the vortex particle separator. The "FLOW CONTROL" valve is used to adjust the back-flush flow rate by bypassing flow from the pump outlet through a bypass loop back to the inlet of the pump.

A relief valve is provided in the unit to protect the pump and electric motor in the event the unit is operated without a regenerative filter attached. The relief valve will open after a 1720 x 10^3 N/m^2 (250 psi) differential is directed across it and will provide a short bypass loop to ensure flow through the pump when the normal flow path is restricted. Without the relief valve, the pump may structurally fail or the motor may overheat, causing a shutdown.

An accumulator is located in the unit for a number of reasons. It provides makeup fluid to the system that may be lost when the quick disconnects are disconnected and connected. It also provides a convenient means of pressurizing the system. The static pressure on the system should range from 138 x 10^3 to 276 x 10^3 N/m^2 (20 psi to 40 psi) for best operating results. This is obtained by first pressurizing the accumulator with air to 138 x 10^3 N/m^2 (20 psi) and then pressurize the system with fluid to 276 x 10^3 N/m^2 (40 psi). The accumulator also provides a dampening effect on the pump pulsations, therefore reducing the induced stresses to the components within the unit.

The secondary filter periodically requires maintenance, which is accomplished by means of quick disconnects and flex hoses located behind the fold-down panel on the side of the unit (see Figure III-6). The secondary filter is identical to the regenerative filter, and thus are interchangeable. The regeneration unit may be used to regenerate the secondary filter. This is accomplished by placing a spare regenerative filter in the system, in place of the normal secondary filter, while regenerating the secondary filter. When installing any of the filters, the matching color coding on the disconnects signifies the proper orientation -- both for regeneration and for the secondary filter installation.

The trap on the vortex particle separator must be cleaned occasionally. To remove the trap, the separator is isolated by disconnecting the "white" quick disconnect on the regenerative filter and the white disconnect on the secondary filter. The clamp is then removed from the trap and the trap is slowly removed. There will be a small amount of spillage due to the static pressure on the fluid but no air will get into the separator. The trap can either be replaced or simply rinsed out, but must be fully charged with

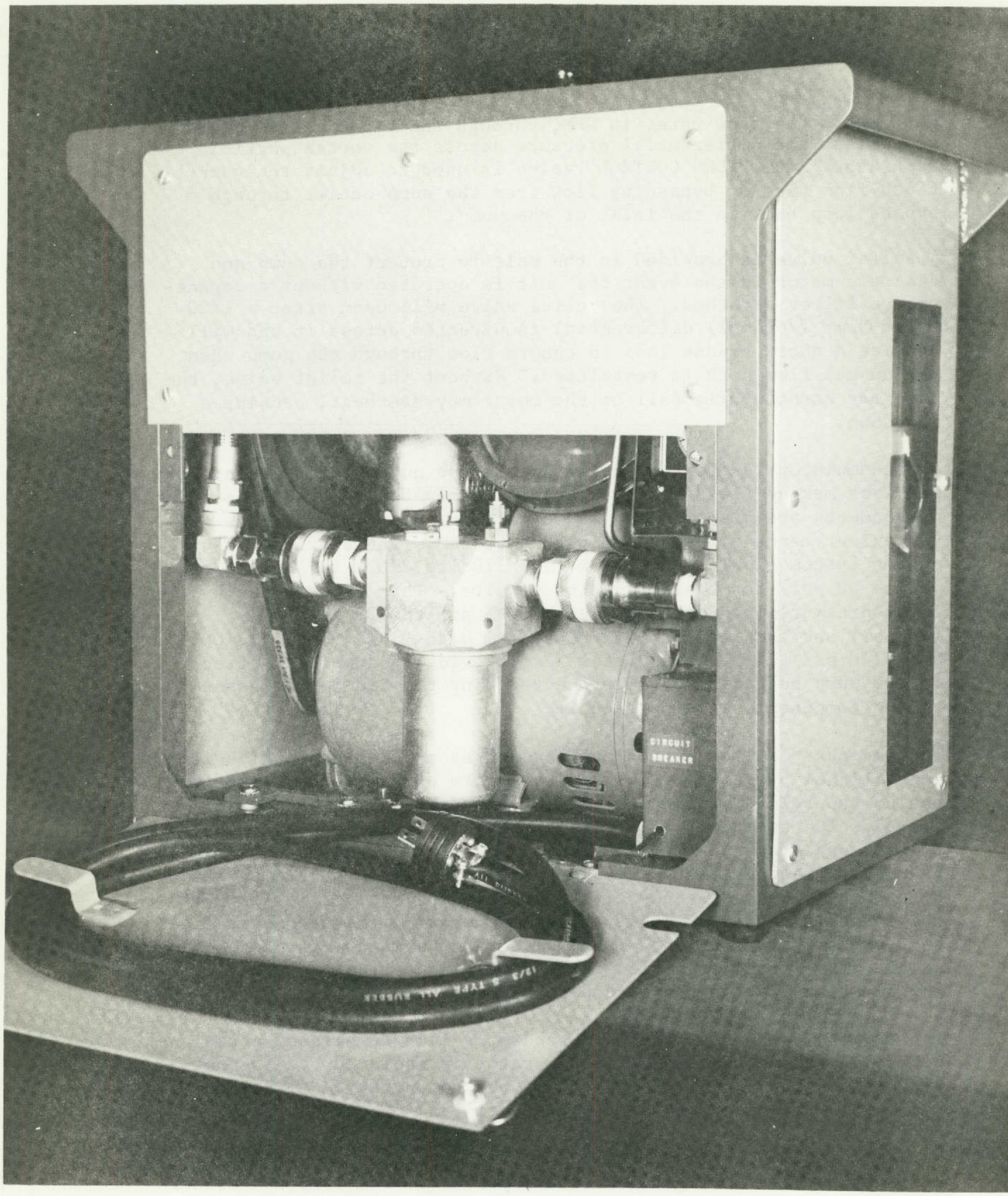

Figure III-6 Interior View - Filter Regeneration Unit

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fluid before attaching to the separator. After attaching, the quick disconnects should be connected and the system pressure should be checked and the system pressurized if required.

The electrical system provides the controls for the pump motor. A low amperage control circuit actuates and times a relay switch for the motor. The main supply requires 115 VAC power with a maximum current of 30 amperes. A 30 amp circuit breaker is included in the filter regeneration unit as well as a 5 amp fuse for the control circuit. All major electrical components are grounded to the frame and into the ground line of the power receptacle. The circuit breaker and fuse are accessible through the fold-down panel on the side of the unit (see Figure III-6). A safety switch is provided on the fold-down panel to prevent operation of the unit while the door is open because of the exposed moving parts of the pump/motor drive.

<u>3. Demonstration Test Panel</u> - The demonstration test panel was designed specifically to demonstrate the operation of the filter regeneration unit, the regenerative filter, and the maintainable filter. A schematic of the demonstration panel is shown in Figure III-7 and a photograph is shown in Figure III-8.

A maintainable filter and a regenerative filter are mounted on the demonstration test panel. The regenerative filter can be attached to the fluid system of the panel by means of the flex hoses and quick disconnects provided. This allows the regenerative filter to be charged with fluid as well as pressurized. If the proper complementary instruments are added, such as a flow meter, ΔP gauge and contaminant injector, the regenerative filter can be loaded with contaminant. The filter regeneration unit is connected to the regenerative filter by means of the color coded disconnects and flex hoses. The regenerative filter is held in place during the regeneration process and, if desired, gauges can be attached to the pressure taps to monitor the differential pressure.

The maintainable filter is hard plumbed into the demonstration panel so that its connect and disconnect characteristics can be demonstrated. The maintainable filter can be charged with fluid to pressures up to 1035×10^3 N/m^2 (150 psi) by charging it with fluid first and then increasing or decreasing the air pressure on the demonstration panel accumulator. The regenerative filter can be pressurized in the same manner. The accumulator in the demonstration panel also provides for fluid makeup when the regenerative filter is connected and disconnected.

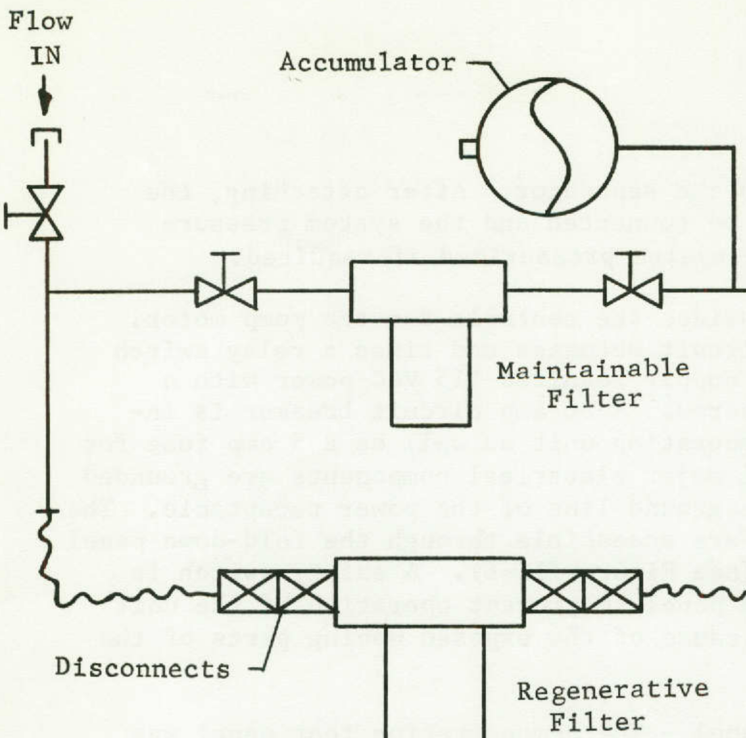

Figure III-7 Demonstration Test Panel Schematic

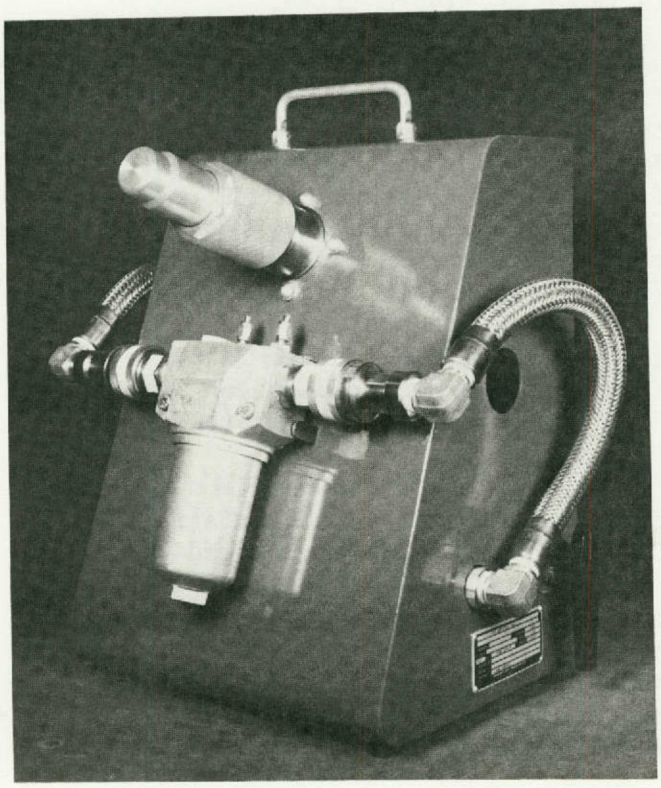

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Figure III-8 Demonstration Test Panel

The demonstration test panel has standard 1/2-inch AN tube female interfaces for fluid supply and return. This provides easy connection to a typical laboratory water supply and drain. Once the demonstration panel is charged with fluid it can be used as a portable demonstration panel by capping off the inlet and outlet lines and using the accumulator to pressurize the lines as required.

D. SYSTEM TRADEOFF STUDIES

A systems compatibility and tradeoff study was conducted to determine what interchangeability was feasible between systems; and also the best approach to regeneration considering portable, fixed, and integral regeneration units. The following discussion outlines the possible configurations and the evaluation considerations for each system. Conclusions are presented at the end of each section.

1. Fluid Compatibility Study - The optimum system for filter regeneration would be one unit that could be used for all fluid filters onboard the spacecraft. With a regeneration unit that uses the working fluid as the backflush medium, this optimum approach is not feasible because of fluid compatibility and bacteria contamination problems. If the regeneration unit is to be used in more than one system, the system fluids must be compatible.

The potable water system must be maintained in a bacteria-free condition, and regeneration units used in other fluid systems cannot be used for the potable water system unless the regeneration unit has been sterilized before use, or the potable water filter is sterilized before returning it to service. Sterilization is necessary to prevent any bacteria from entering the potable water system and contaminating it. Hot water sterilization techniques could be designed into the regeneration unit, but it would add to the complexity and use of the unit. The development filter regeneration unit does not contain any provisions for sterilization.

The process water system is relatively dirty and contains soap, etc. The thermal water system is a closed loop system and will accumulate contamination over a period of time that would not be filtered out. It would not be desirable to transfer residual water from either of these systems to the potable water system.

It is recommended that any regeneration unit used for potable water be used only for potable water. It is feasible, however, to regenerate the filters from the potable water system and then use them in the process water or thermal water systems, or as a backup for the secondary filter in the regeneration unit.

The same regeneration unit could be used on both the process water and the thermal water systems. The particulate requirements for both systems are identical. Thus, a regeneration system capable of maintaining that cleanliness could be used in either system. The possibility of transferring a small amount of water from one system to the other exists. The addition of process water to cooling water may cause the growth of bacteria in the cooling system. If that proves to be a problem, an inhibitor could be added. The inhibitor in the cooling system should be non-toxic so the addition of any thermal water to the process water should not create a problem.

The Freon-21 system should be isolated from the water systems for several reasons. Freon-21 is a toxic liquid so the likelihood of contact or loss should be minimized. If a regeneration unit were to be used on a water system as well as Freon-21, the unit would have to be purged before each use. The equipment required to accomplish a purging operation would weigh as much as the regeneration unit and is not recommended. A purging operation with Freon-21 would greatly increase the chance for leakage or contact. The solubility of Freon-21 in water and water in Freon-21 are both very low, therefore, only a small amount of Freon contamination would be necessary before a mixture rather than solution would exist. Water in the Freon-21 loop will freeze out, damaging the system. Freon-21 in the process water system may eventually enter the potable water system and thus contaminate it.

2. Regeneration System Configurations Study - Regeneration systems can be classified by mode of operation and the component configuration. The mode of operation may be one of three types: (1) system installation, (2) portable, or (3) fixed -- with the filter brought to the system. The three modes are illustrated in Figures III-9, III-10 and III-11.

The "system installation" mode of operation, Figure III-9, is the only mode that would allow the regeneration to be automatically started and stopped. It does not require that the regeneration unit be manually connected to the system for each operation, and does not require removal of the filter. This mode of operation would be advantageous for systems that require frequent regeneration or have hazardous fluid handling problems. One disadvantage of this mode is that it only maintains one filter, and to use it for more than one filter would require a complex valving arrangement. Also the spacecraft system must have sufficient flow rate

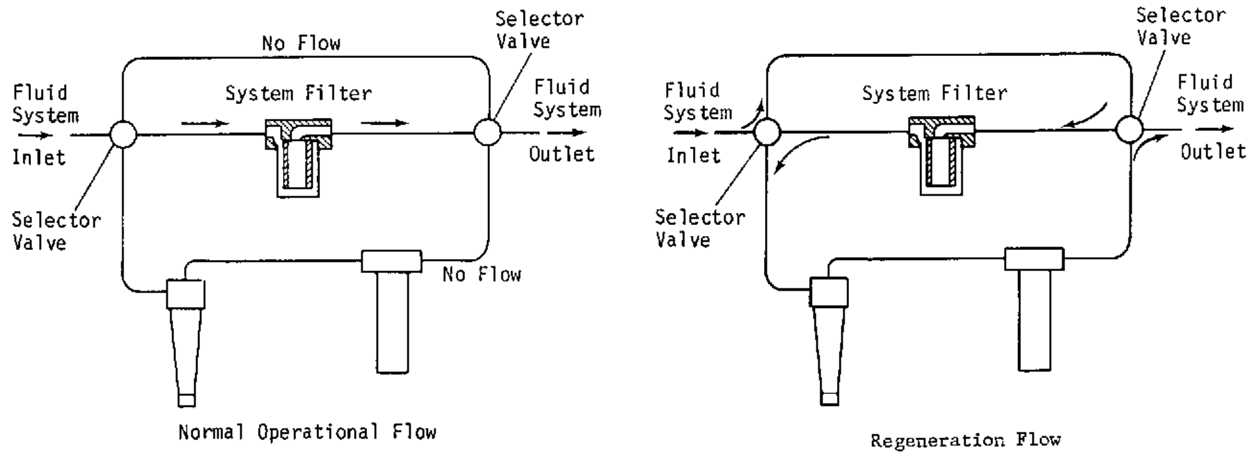


Figure III-9 System Installation

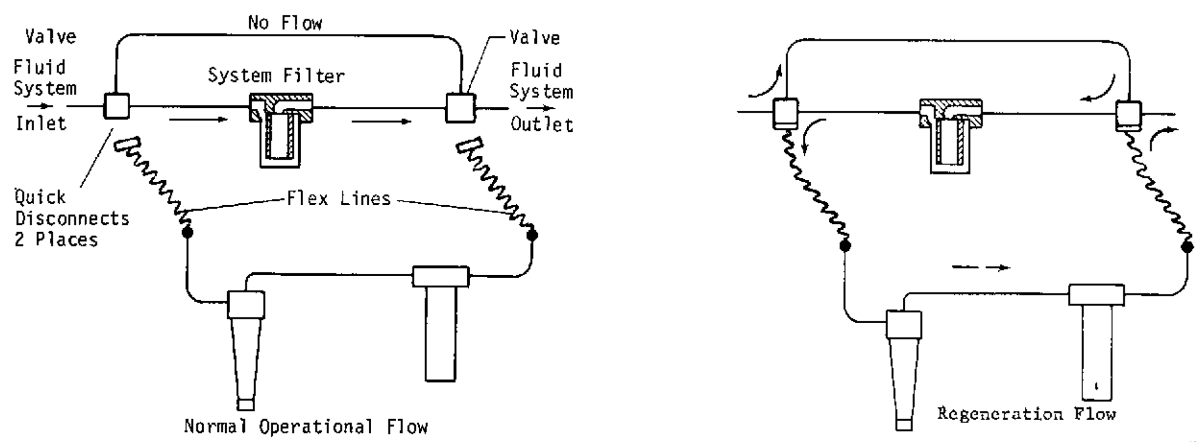


Figure III-10 Portable Installation

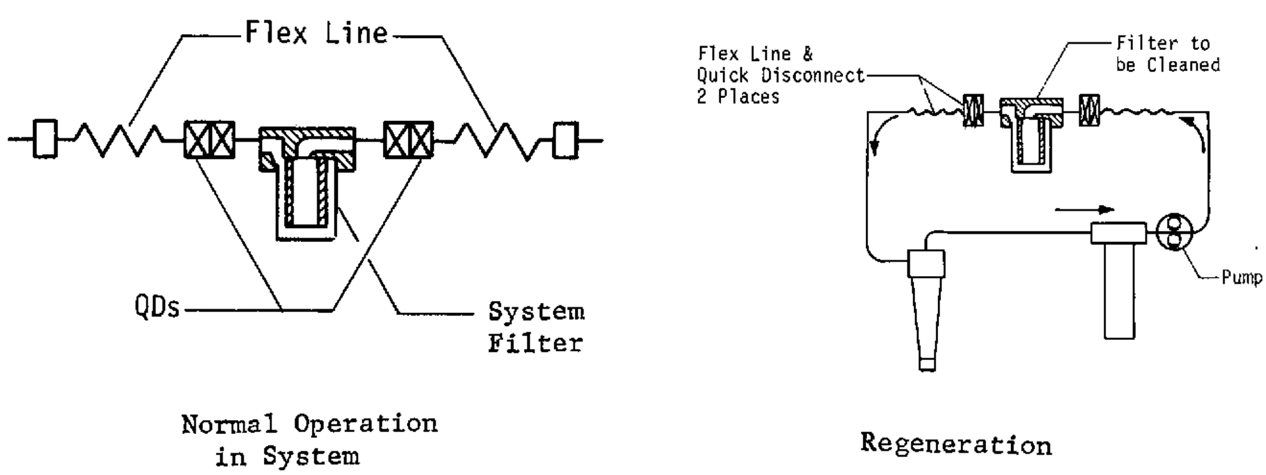


Figure III-11 Fixed Installation

($6.31 \times 10^{-4}\ m^3/sec$, 10 GPM) and pressure to operate in the regeneration mode; however, a pump could be added to the system to overcome this problem.

The "portable" mode of operation, Figure III-10, requires that the regeneration unit be manually connected to the system. This mode allows the use of the same regeneration unit for other filters in the same, or compatible systems. The crew time required for this mode of operation would be greater than the "system installation".

The "fixed" mode of operation, Figure III-11, requires that the filter be removed from the system and brought to the regeneration unit. A new or previously regenerated filter could be placed in the system, the system could be shut down, or the filter bypassed while the filter was being regenerated. If the filter was replaced, the system would be shut down only for time required for the filter change. This mode of operation would allow many filters from the same or compatible systems to be regenerated with the same unit. The crew time requirement for this mode would be greater than the other modes but the regeneration time could be scheduled if the filter was replaced.

It is possible to combine several modes of operation in one regeneration unit. For example, a unit could be portable to most systems but normally attached to one system where it would operate in the systems installation mode. It could also operate as a fixed unit with filters being attached to it.

The component configuration of the regeneration unit may be varied in seven different ways as shown below. Figure III-12 shows a portable unit, but the same configuration could be achieved with a "system installation" mode with increased valving.

Portable with Pump - This configuration requires that the system be shut down for regeneration. The regeneration unit may then be attached or the proper valves opened and the regeneration process started. The configuration has a self-contained pump which means that the system does not need to be operating during the regeneration. This configuration also has a simple valving arrangement and is essentially the configuration of the fixed mode of operation.

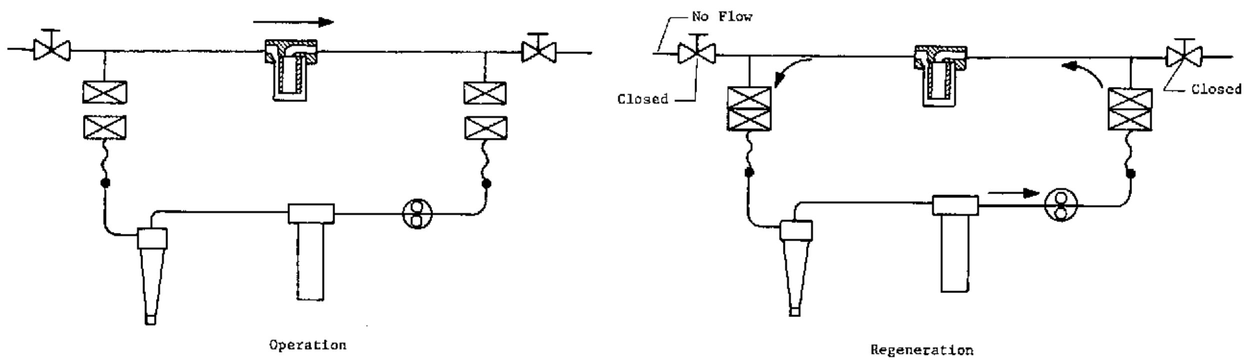


Figure III-12 Portable with Pump

Portable with Bypass and No Pump - This configuration uses the system pump, rather than a pump in the regeneration unit, to provide the power for the regeneration process. This means that the spacecraft system does not need to be shut down. The disadvantage of this configuration is that the regeneration unit is not a self-contained unit and the spacecraft subsystem must meet the requirement for a high flow rate backflush. This requirement cannot be satisfied by all systems.

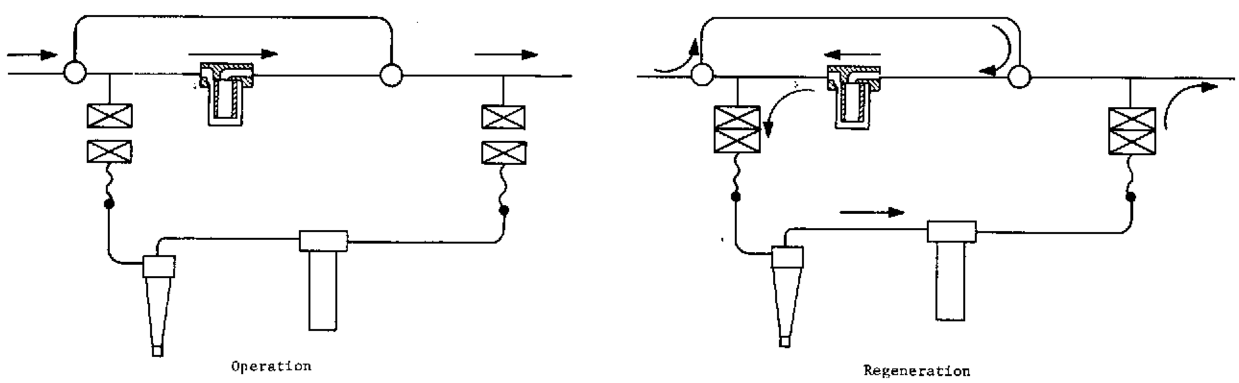


Figure III-13 Portable with Bypass and No Pump

Portable with Bypass and Pump - This configuration does not require the system to be shut down or operating, and no additional load is placed on the system during regeneration. The configuration requires a pump, and during regeneration the system fluid is unfiltered unless a redundant filter is placed in the bypass loop.

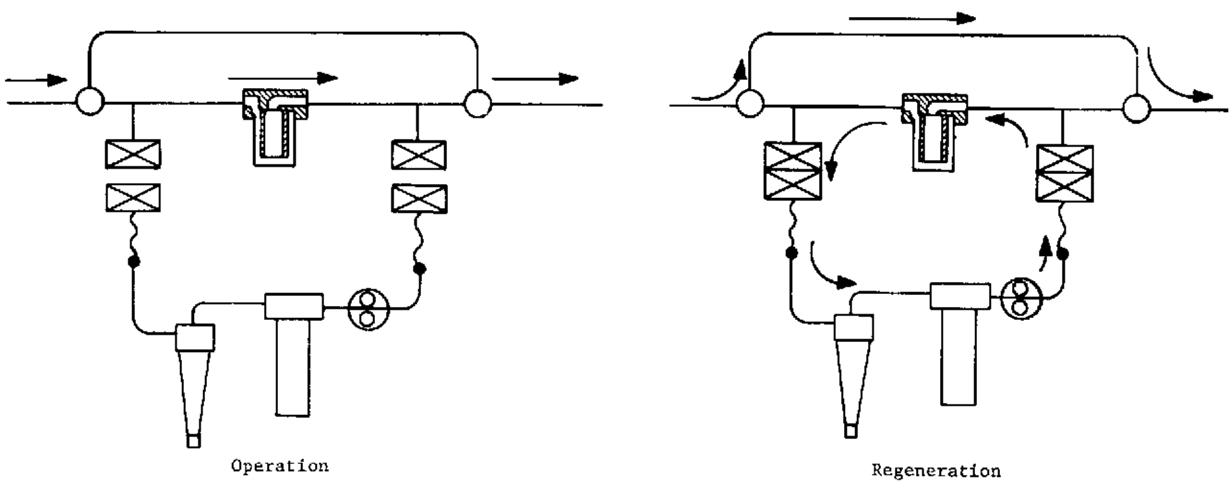


Figure III-14 Portable with Bypass and Pump

Redundant with Pump - This configuration is very similar to the portable with bypass-pump configuration, with the addition of a filter in the bypass. This allows a redundancy of filters as well as providing a filter for the fluid during regeneration.

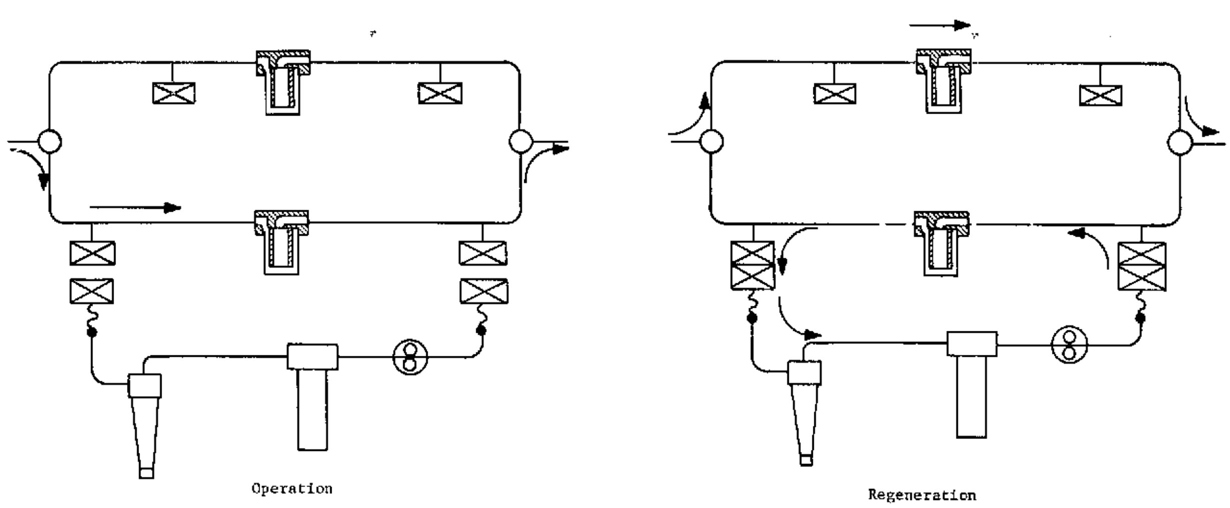


Figure III-15 Redundant Filters with Pump

Redundant Filters with No Pump - This configuration is similar to the protable-no pump configuration except for the redundant filter. The redundant filter will allow the system to operate should one filter clog, but does not affect the regeneration process.

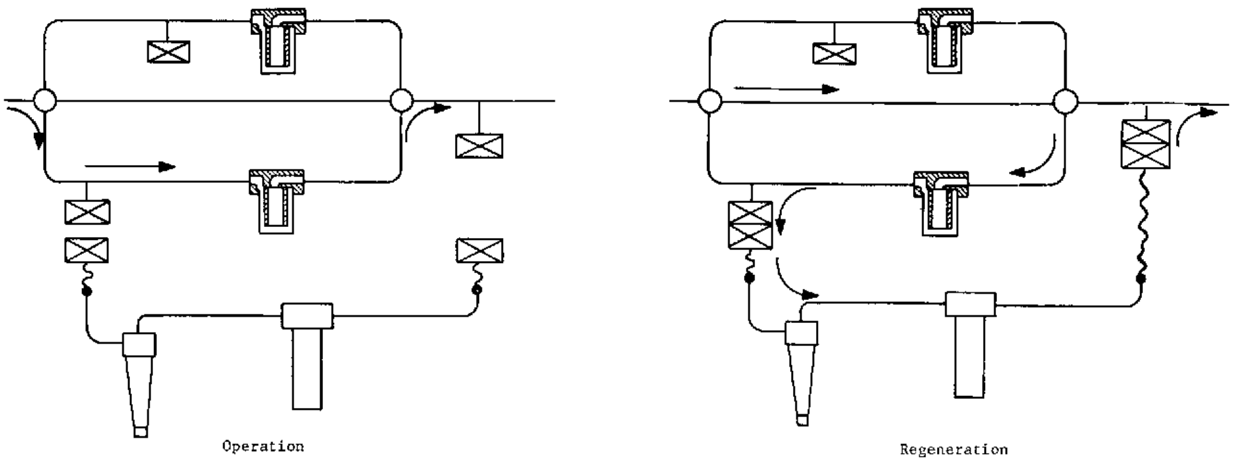


Figure III-16 Redundant Filters - No Pump

No Regeneration Unit Filter and No Pump - This configuration allows reduction in the number of components in the regeneration unit. The fluid flow during regeneration is identical to the redundant and portable systems. This system provides a filtered flow at all times, but a flow through the system is required by the spacecraft system.

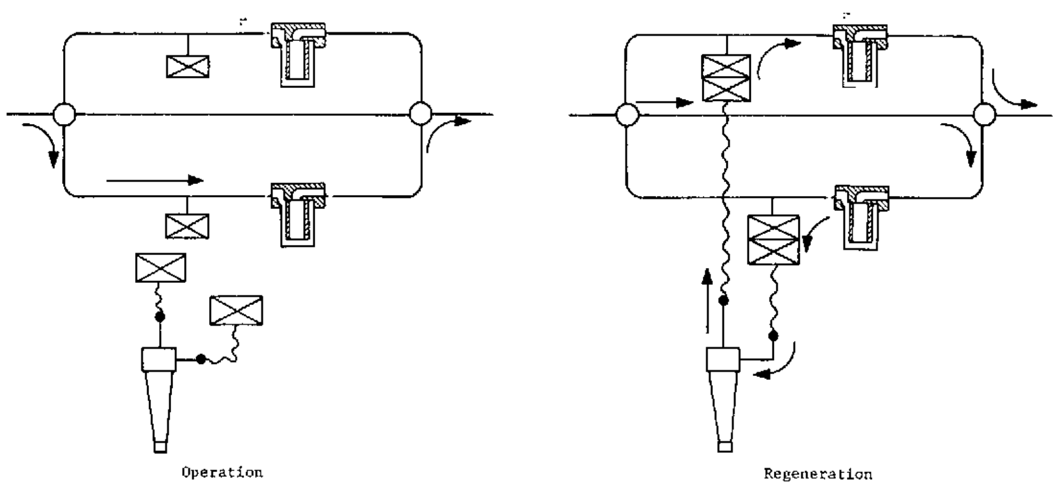


Figure III-17 Simplified Unit

No Regeneration Unit Filter but With Pump - The flow arrangement with this regeneration unit is similar to the "portable with pump" configuration. The difference is that a redundant filter is in the system to provide flow should one filter clog. The system must also be shut down to regenerate a filter with this configuration.

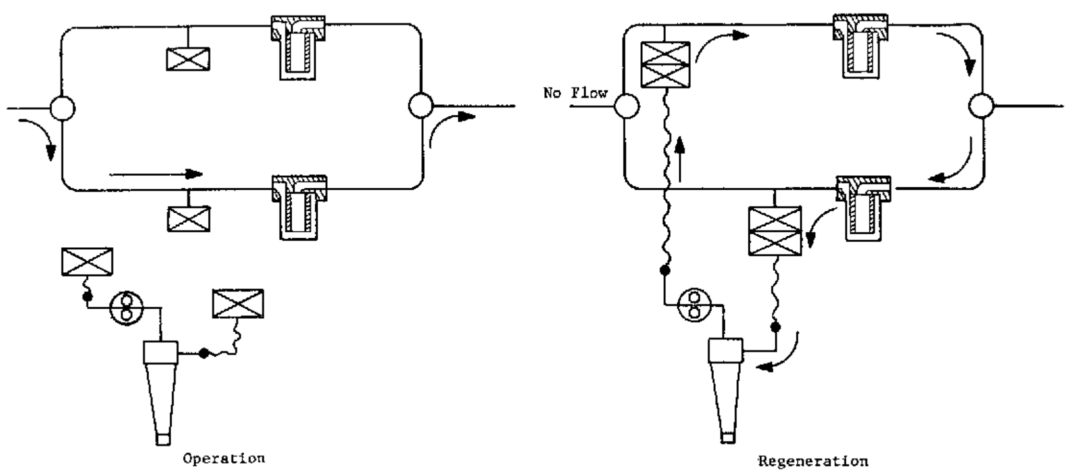


Figure III-18 Simplified Unit with Pump

3. Regeneration System Selection Study - The pressure drop and flow rate of the filter regeneration system is relatively large as compared to most spacecraft fluid systems. This would indicate that the fluid system pumps would not normally be designed such that it would meet the requirements of the regeneration system. Since the backflush/jet impingement configuration and the vortex particle separator design require a specified flow rate for proper operation -- with a commensurate pressure drop; it is not logical that many fluid systems could meet all of these specific requirements.

Since it is not practical to supply a booster pump for each and every spacecraft fluid system, the pump should be self-contained within the filter regeneration unit. This criteria restricts the filter regeneration system to the following four systems:

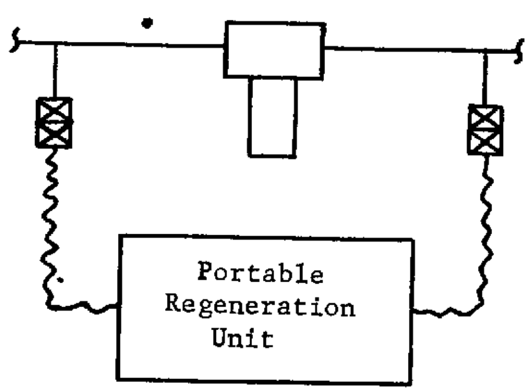
Portable with pump
Portable with by-pass and pump
Redundant filters with pump
Simplified unit with pump

The requirement for redundant filters or bypass loops is actually determined by the spacecraft system mode of operation, criticality, or reliability. Therefore, the regeneration system should not place this type of constraint upon the system. This leaves a regeneration configuration that is self-contained and either portable or fixed.

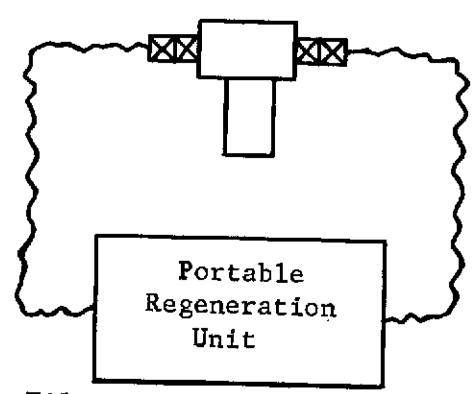
The portable or fixed regeneration units each have their different characteristics. The fixed unit would be permanently installed in a designated maintenance area where filters would be completely removed from their respective systems and taken to the unit for cleaning. This requires special quick disconnects on the filters to properly interface with both the fluid system and the fixed regeneration unit. A similar concept would eliminate these two quick disconnects, which impose additional pressure drop on the spacecraft system. This concept involves a removable filter canister from the system which fits into the fixed regeneration unit. With this method, only one means of connection is required.

The portable concept requires an interface with each of the fluid systems. This can be as simple as two quick disconnects and an electrical outlet. If designed properly, the regeneration unit could service two or more fluid systems from one location. The filter is not removable so no quick disconnects are located in the normal fluid system flow path whereas the fixed unit does. The portable unit therefore imposes less constraints on the fluid system, lower overall system pressure drop, and a less complex interface.

The conclusion is that the fixed system with the removable filter canister is by far the best concept, but since the removable canister type filter is only in a concept stage and requires significant design and development, a more practical conclusion is that the portable regeneration unit is best. The advantages of the portable unit are: (1) minimum interface requirements for the individual fluid systems, and (2) minimum pressure drop. The portable unit could also be used as a fixed type of unit by providing the capability of backflushing a filter that has been removed from another system (see Figure III-19).



Filter in System



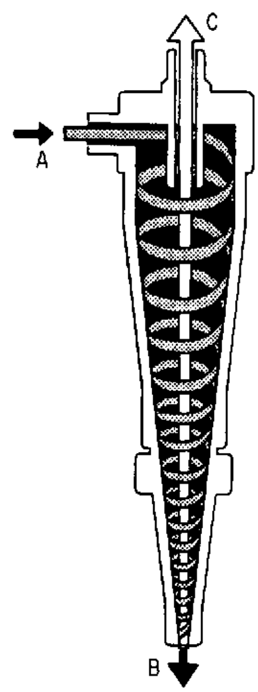
Filter Removed from System

Figure III-19 Portable Concept with Fixed Concept Capabilities

E. DESIGN ANALYSIS

1. Vortex Separator Theory - Vortex particle separators are simple passive devices which separate chemically inactive mixtures of substances of differing densities by the action of centrifugal forces induced by swirling flows.

The operation of a vortex separator involves the tangential injection of the fluid and entrained particles at the inlet (A) into the cylindrical section causing a vortex motion. The vortex motion creates centrifugal forces up to or greater than 10,000 times the force of gravity. The centrifugal forces cause the heavier substance to move to the outside wall of the separator. The lighter fluid remains in the center of the cylinder and is withdrawn from the overflow (C) at one end of the cylinder. The heavier substance is moved along the wall downwards in a spiral motion towards the underflow outlet (B) of the conical section by a decreasing static pressure gradient and is discharged out the tube into the particle collector. The pressure gradient is increased by the conical section which causes an increasing tangential velocity. Since the increase in velocity comes from a decrease in static pressure, the decreasing static pressure gradient towards the underflow is pronounced. The increased tangential velocity also increases the centrifugal forces and thus the separation.



Ter Linden and Van Dongen (Ref. 1) found the variation of static pressure P_s and total (static and dynamic) pressure P_t at various points in the separator as shown in Figure III-20. Pressure in the separator is high near the walls and low in the turbulent core in the center. The pressure is highest at the inlet and lowest at the apex (point B) of the separator. The static pressure decreases in the direction of the apex creating a flow towards the apex.

The fluid flow in a vortex separator is three-dimensional and very complex. The velocity at every point in the separator may be resolved into three components; tangential, radial, and axial. The

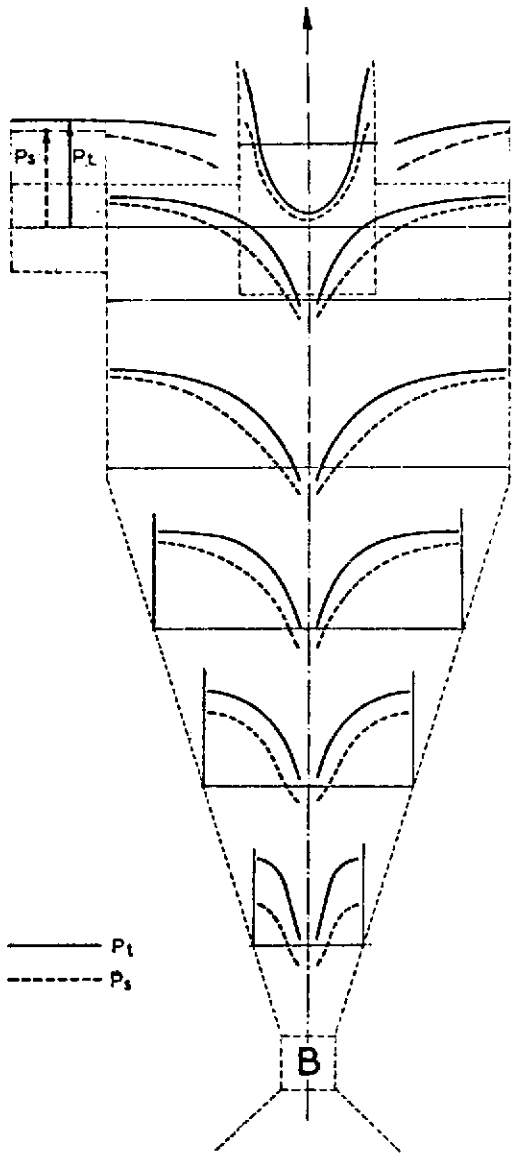


Figure III-20 Total and Static Pressures (P_t and P_s) at Different Points in a Vortex Separator

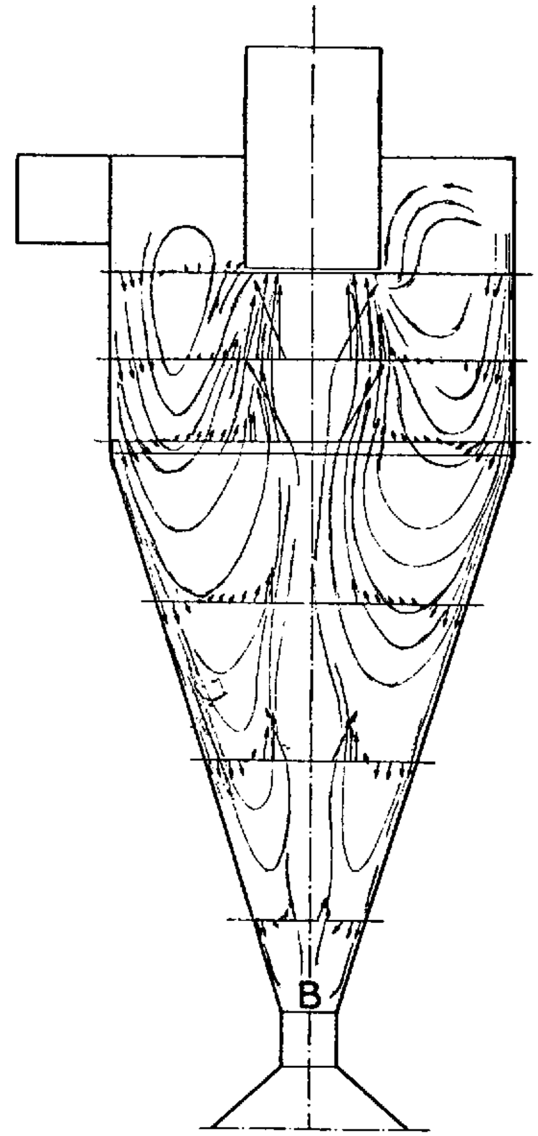


Figure III-21 Secondary Streamlines in a Vortex Separator tangential velocity predominates throughout the entire separator except in the highly turbulent core where the axial component prevails. The axial velocity is directed towards the apex along the walls and in the opposite direction in the center. The flow along the walls moves the particles to the outlet port. The central flow in the unstable core may transport particles from the lower part of the separator to the exhaust, and these entrainment-type flows are often called secondary flows. The radial component is directed toward the center of the vortex throughout most of the separator and opposes the centrifugal action caused by the tangential velocity. To obtain a high particle separation efficiency, re-entrainment of particles into the central core must be minimized. To accomplish this, the centrifugal action must be greater than the radial velocity, and thus the tangential velocity must be as large as possible compared to the radial velocity.

If the radial and axial velocity components are resolved, an insight may be gained into the secondary flows in a vortex separator. Figure III-21 shows these secondary flows inside a separator of conventional shape. These flows cause the undesirable transfer of particles to the overflow exhaust.

There are two basic equations which describe the flow in a vortex:

(1) $$\frac{V_t}{V_o} = \left(\frac{R_o}{R}\right)^n$$ - spiral velocity

(2) $$A = \frac{V_t^{\,2}}{R}$$ - centrifugal acceleration

where: V_t = tangential velocity

V_o = inlet velocity

R = local separator radius

R_o = maximum separator radius

A = centrifugal acceleration

n = 0.5 to 0.7 (determined by tests)

The first equation shows that the tangential velocity increases with a decrease in radius but that in practice the rate of velocity change is less than the rate of radius change. The equation also shows that the tangential velocity may be increased by increasing the inlet velocity. The second equation indicates that centrifugal acceleration, the separating force in a vortex separator, may be increased either by increasing the tangential velocity or decreasing the radius. Thus, the separating force is increased by increasing the inlet velocity or decreasing the separator radius, either local or maximum.

Stokes Law governs the settling velocity of small spherical bodies settling in a viscous fluid and is the basic law that describes the separation of masses with different densities in a vortex separator. The equation for Stokes Law is:

$$(3) \quad V_s = \frac{g\, D^2}{18\mu} (\rho_p - \rho)$$

where: V_s = settling velocity

μ = fluid viscosity

g = acceleration force in the settling direction

D = particle diameter

ρ_p = particle density

ρ = fluid density

The law shows that only particles heavier than the fluid will move to the outside wall of a cyclone and that the greater the difference in density, the higher the velocity. Thus, as the density of the particle approaches the density of the fluid, separation becomes increasingly difficult. The law also indicates that the lower the fluid viscosity, the higher the velocity and therefore, increased separation.

As the specific gravity of a contaminant approaches 1.0, separation efficiency decreases. If the values are equal to or less than one, separation will not occur in a separator designed for contaminants with a specific gravity greater than one. Preliminary testing of over 50 different types of food indicated that about 80% of them had a density greater than water. This indicates that it should be possible to separate these particles from water with a vortex particle separator.

An equation for the minimum particle diameter that should be completely separated from the fluid in a vortex separator can be derived from Stokes Law by assuming the fluid undergoes a fixed number of turns at a constant spiral velocity with no mixing.

From basic mechanics,

$$\text{distance} = \text{velocity} \times \text{time or time} = \frac{\text{distance}}{\text{velocity}}$$

$$(4) \quad B = V_s \times T$$

$$(5) \quad T = \frac{N_e \; 2\pi R}{V_t}$$

where: B = separator inlet width = maximum horizontal distance a particle must travel

N_e = effective number of turns

T = time for spiral flow

Substituting equations (2), (3) and (5) into (4) with

$$g = A = \frac{V_t^{\,2}}{R}$$

and $$V_t = V_c$$

$$B = \left[\frac{1}{18\mu} \left(\frac{V_c^{\,2}}{R}\right) D^2_{min} \left(\rho_p - \rho\right)\right]\left[\frac{N_e \; 2\pi R}{V_c}\right]$$

Solving for minimum particle diameter

$$(6) \quad D_{min} = \left[\frac{9\mu \; B}{\pi N_e V_c \left(\rho_p - \rho\right)}\right]^{0.5}$$

Smaller particles will be removed to an extent proportional to their initial distance from the wall. The literature indicates N_e to vary between 2 and 10 depending on separator design and operating conditions with $N_e = 5$ being a reasonable approximation. This equation suggests several design factors. Better separation may be obtained by decreasing the width of the inlet to the separator. This decreases the distance a particle must travel to the wall of the separator. Because of the decrease in the distance a particle must travel, smaller particles with their lower settling velocity can travel that distance in a given amount of time. The length of time available for settling can be increased by increasing the effective number of turns. This allows more time for particles with lower settling velocities to reach the wall. Increasing the inlet velocity decreases the minimum particle size separated since it increases the centrifugal force at a faster rate than it decreases the settling time.

It is also quite evident from this equation, that equations of performance characteristics of vortex separators must be tempered by test results due to the complexity of the vortex flow.

From boundary layer theory an equation may be derived relating the separator shape and the effect of gravity on the pressure gradient. The pressure gradient is the force that causes the flow of solids down the separator wall. The equation is:

$$(7) \quad \frac{dP}{dX} = \frac{R_o}{R}\frac{dR}{dX}\left(\frac{V_t}{V_o}\right)^2 \pm \frac{gL}{V_o^2}\sqrt{1 - \left(\frac{R_o}{L}\right)^2\left(\frac{dR}{dX}\right)^2}$$

where: P = pressure

X = distance along wall

L = length of the cone wall

This equation indicates two methods to negate the effect of gravity on the pressure gradient. One method is to design the separator such that $\left(\frac{R_o}{L}\right)^2\left(\frac{dR}{dX}\right) = 1$ which for a cone reduces to $\frac{R_o}{L} = \pm 1$,

which equates to a flat plate. However, a flat plate is not an efficient shape for a vortex separator. The second method to negate the effect of gravity is to maintain an inlet velocity such that $V_o > \sqrt{gL}$ such that $\frac{gL}{V_o^2} << 1$. Thus for a separator with a

conical wall length of L = 30 cm, V_o should be greater than 17.2 cm/sec which is not impractical. Since 6 m/sec is a reasonable inlet velocity for a water-solid separator, $\frac{gL}{V_o^2}$ can be made equal to 0.08.

Thus, the effect of gravity can be negated.

It is also evident from equation (7) that in zero gravity operation, a pressure gradient still exists. The pressure gradient is a function of separator design, inlet velocity, and location in the separator.

E

2. Separator Redesign Analysis - During the course of the program, it was necessary to redesign the separator because the pressure drop of the separator used for development testing was greater than desired at the increased prototype regeneration unit flow rate. In order to maintain a specific separator efficiency but shift it to a different flow rate, the inlet area is adjusted to maintain the same inlet velocity. The remaining dimensions are determined from the inlet diameter and ratios of the various dimensions. This technique was used to adjust the performance characteristics of the separator to 6.31×10^{-4} m^3/sec (10.0 gpm) from 4.55×10^{-4} m^3/sec (7.2 gpm). However, rather than using strictly the ratios from the test separator, an average of ratios of the Taylorator series of separators was used. These ratios are shown in Figure III-22.

In order to obtain the dimensions of the new separator, the inlet diameter was calculated to provide a velocity of 7.72 meter/sec at the design flow rate of 6.31×10^{-4} m^3/sec (10.0 gpm). From the inlet diameter, the main body diameter was calculated and used as the basis for determining the remaining dimensions. The average ratios produced an overflow diameter which was smaller than the inlet. To prevent the overflow from restricting the flow and causing an increase in pressure, the overflow diameter was increased to 1.09 cm. The initial testing indicated a pressure drop greater than anticipated. In order to reduce the pressure drop, the overflow was enlarged to 1.32 cm. The internal dimensions of the separator and a comparison with the test separator are shown in Figure III-23.

The separator was constructed of plexiglass and polished such that the operation of the separator could be observed. Stress calculations were performed to insure that the separator would withstand a pressure of 1.375×10^6 N/m^2 (200 psi). During performance testing the pressure on the separator has reached 1.72×10^6 N/m^2 (250 psi) with no failures.

3. Freon-21 Performance Analysis - The operation of a fluid system with Freon-21 presents a number of problems not associated with a water system. The most significant problem of Freon-21 is its incompatibility with the seals and materials normally used in water systems. Thus, in order to test a Freon-21 system, it would be necessary to use components with Freon-21 compatible materials. This would have increased the expense over that of a prototype water regeneration system. In addition, the test fixtures used for development and performance testing are not suitable for Freon testing. Such testing would require a closed loop system with a Freon-21 compatible pump. The separator for the prototype hardware could not be used in a Freon-21 system as it is constructed from plexiglass, a non-compatible material.

Separator	Velocity m/sec @ 207 x 10^3 newton/m^2	I/D	d/D	L_2/D	L_1/D	O/D	L_3/D	L_4/D
AC-2[1]	7.85	.192	.174	2.59	1.17	.122	.328	.304
AP-2[1] AR-2[1]	8.60	.188	.178	2.67	1.20	.125	--	.314
BC-2[1]	7.30	.167	.167	2.43	1.14	.133	.86	.298
BP-2[1] BR-2[1]	7.13	.167	.167	2.40	1.14	.167	.312	.300
Average	7.72	.178	.172	2.52	1.16	.128	.314	.304
Measure B-2[1]	6.87	.168	.206	2.30	1.16	.0935	.13	.295

1. Taylorator Type

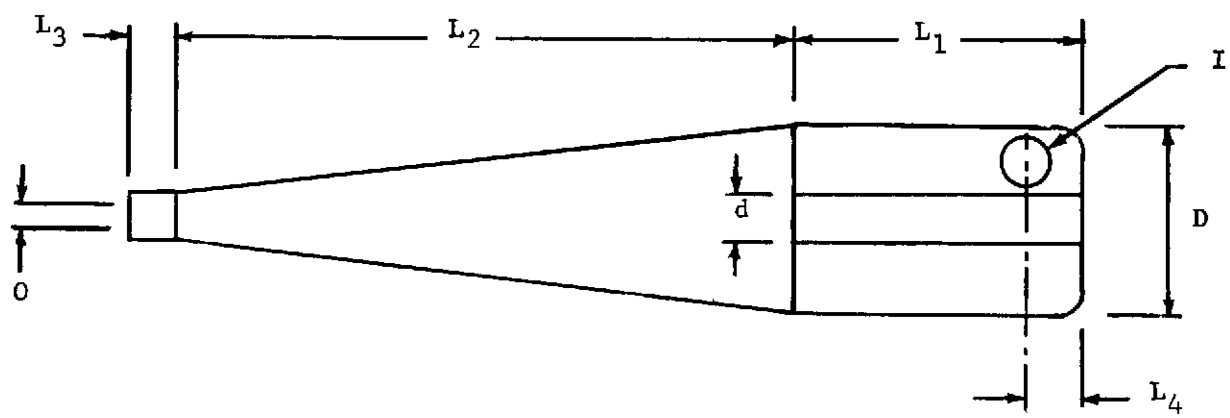
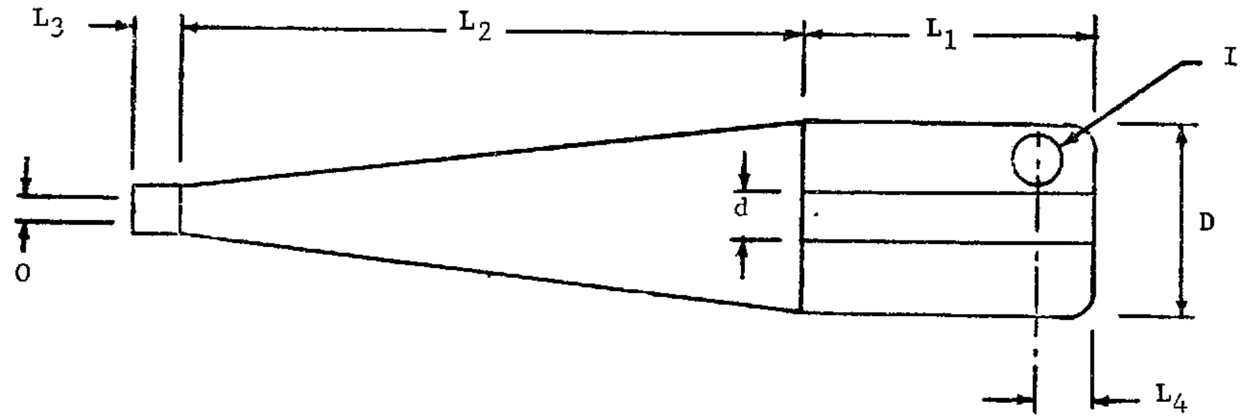


Figure III-22 Separator Dimensional Ratios



Separator	L_1	L_2	L_3	L_4	D	d	I	O
Prototype	6.73	14.4	.736	1.73	5.69	1.32	1.02	.728
Test	6.30	12.5	.714	1.63	5.44	1.12	.915	.508

Note: Dimensions in centimeters

Figure III-23 Dimensions of Prototype Particle Separator

Since it was not practical during this program to conduct any development testing with Freon-21, an analysis of the theoretical performance difference between Freon-21 and water was performed. The analysis covered four areas: (1) settling velocity, (2) relative pressure drop, (3) power requirement, and (4) filter cleaning ability (impulse).

The settling velocity of Freon-21 and water was compared using Stoke's Law:

$$V_s = \frac{gD^2}{18\mu} (\rho_p - \rho)$$

where: V_s = settling velocity

μ = fluid viscosity

g = acceleration in the settling direction

D = particle diameter

ρ_p = particle density

ρ = fluid density

The prime (^{1}) quantities are those referring to Freon-21. Calculating the ratio of the Freon-21 settling velocity to the water velocity (V_s^1/V_s) and using the specific gravity relative to water (S), the following is obtained.

$$V_s^1/V_s = \frac{\mu(S_p - S^1)}{\mu^1 (S_p - 1)}$$

where: S^1 = 1.38 (Freon-21)

μ^1 = 0.342 centipoise (Freon-21)

μ = .95 centipoise (water)

The results of this equation are shown in Figure III-24. The contaminant used for the development testing has a specific gravity of about 2.6. A particle with that specific gravity has a settling velocity in Freon-21 that is 112% greater than that in water.

The relative pressure drop of Freon-21 as compared to water was calculated by assuming a constant flow rate of 6.31×10^{-4} m^3/sec and a pressure drop proportional to the pressure drop determined from equivalent lengths of tubing having an inside diameter of 1.07 cm. The Reynolds number:

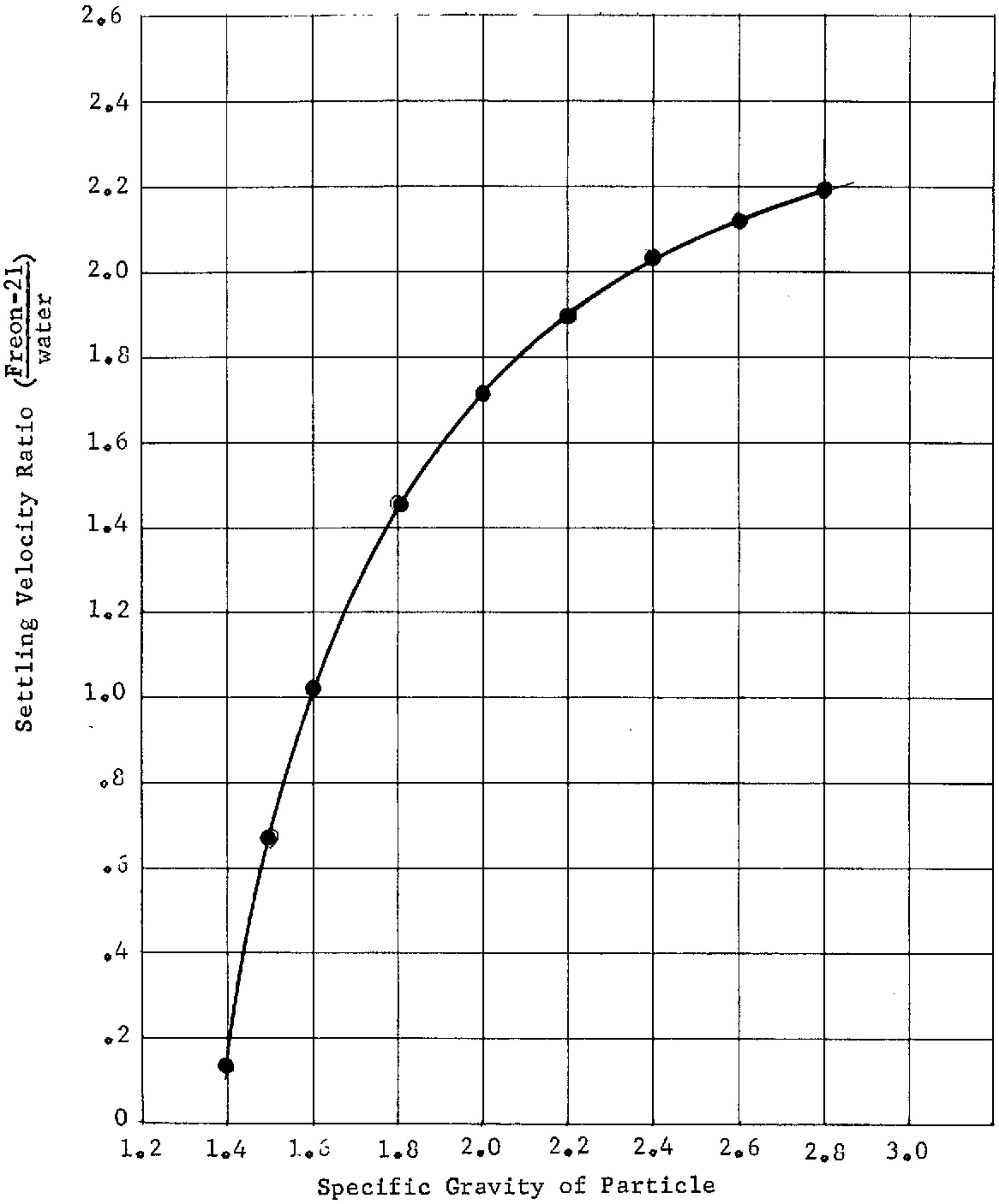


Figure III-24 Settling Velocity Ratio vs Specific Gravity

$$Re = \frac{Dv\rho}{\mu}$$

where: D = internal diameter

v = mean velocity

ρ = density

μ = absolute viscosity

was first calculated and used to determine the friction factors of both fluids. The relative pressure drop was then determined by taking the ratio of the pressure drops obtained from Darcy's formula:

$$\Delta P = \frac{\rho f L v^2}{D \ 2g}$$

where: ΔP = pressure drop

f = friction factor

L = equivalent length

g = acceleration of gravity

At a flow rate of 6.31×10^{-4} m^3/sec, the velocity in a tube with an inside diameter of 1.07 cm was determined to be 7.05 m/sec. The Reynolds numbers were calculated using the density $\rho^1 = 1.38 \times 10^3$ kg/m^3 and viscosity $\mu^1 = 3.42 \times 10^{-4}$ N $\cdot$ s/m^2 for Freon-21 and density = 10^3 kg/m^3 and viscosity = 9.5×10^{-4} N $\cdot$ s/m^2 for water. Using these figures, the Reynolds number for Freon-21 is Re = 3.02×10^5 and for water Re = 7.88×10^4. The relative roughness ($\epsilon = \frac{E}{D}$, where E is absolute roughness) of the tubing was calculated to be 1.43×10^{-4}. Using this data, the friction factors were determined to be f = 1.55×10^{-2} for Freon-21 and f = 1.97×10^{-2} for water.

In taking the ratio of the pressure drop for Freon-21 to water, Darcy's formula reduces to:

$$\frac{\Delta P^1}{\Delta P} = \frac{f^1 \ \rho^1}{f \rho}$$

Substituting the values determined above, the pressure drop for Freon-21 is found to be 8% greater than that of water.

The power increase for the operation of a system on Freon-21 as compared to water is identical to the increased pressure, provided the flow rate is the same. Since power is equal to flow rate times pressure (watts = Q x P), for a constant flow rate, the power increase is directly proportional to the pressure increase. On that basis, the power requirement for Freon-21 would be 8% greater than that of water.

An estimate of the backflush cleaning ability is based on the assumption that cleaning ability is directly proportional to the impulse of the fluid. However, the solvent properties of Freon-21 should enhance its cleaning ability. The equation for the impulse (F_T) may be written as:

$$F_T = (P + V^2) A$$

where: A = area being acted upon
V = fluid velocity
P = fluid pressure

Taking the ratio of Freon-21 to water, assuming a pressure drop across the filter of 103×10^3 N/m^2 (15 psi), and using the previously obtained data, the cleaning ability of Freon-21 is approximately 17.5% greater than that of water.

The results show that operation of a regeneration unit with Freon-21 is possible at a power requirement that is slightly greater than that of water. Because Freon-21 has a greater cleaning ability and produces a higher settling velocity, it should be possible to reduce the flow rate and pressure drop in the separator. By doing this, the total pressure drop and power requirement may be reduced below that of a water-based regeneration unit.

4. Regeneration Unit Design Analysis - A pressure drop analysis was conducted to determine system sizing and pump characteristics for the filter regeneration unit. This analysis was performed using vendor data on the components in the system, and by estimating the overall system layout. The pressure drop data was calculated, extrapolated from known data, or determined by actual testing. Table III-5 lists the sources of pressure drop and how the pressure drop was determined. Figure III-25 shows this data in graphical form for the individual components, and Figure III-26 shows the overall system pressure drop. An additional pressure drop will occur when the secondary filter becomes loaded due to normal use. This added pressure has been determined from testing to be approximately 69×10^3 N/m^2 (10 psi) at 4.29×10^{-4} m^3/sec (6.8 GPM). This is shown on the graph in Figure III-26 and has been extrapolated out to 8.2×10^{-4} m^3/sec (13 GPM). The baseline flow rate was not known at the time the design calculations

Table III-5 Pressure Drop Data

Item	Qty.	Source of Data	Total ΔP in N/m^2 (psi)		
			4.41×10^{-4} m^3/sec (7 GPM)	6.31×10^{-4} m^3/sec (10 GPM)	82×10^{-4} m^3/sec (13 GPM)
Quick Dis-connects	4 Sets	Converted vendor data	113×10^3 (16.4)		435×10^3 (63.1)
Pipe Elbows Pipe Tees	9	Calculated	117×10^3 (17.0		393×10^3 (57.0)
Flex Hoses 2 at .762 m (2.5 ft) 2 at .228 m (.75 ft)	4	Calculated	78.5×10^3 (11.4)		262×10^3 (38.1)
Separator	1	Extrapolated from known size sepa-rator data	103×10^3 (15.0)	207×10^3 (30.0)	317×10^3 (46.0)
Regenerative Filter, normal flow	1	Actual test data	75.6×10^3 (11.0)	158×10^3 (23.0)	255×10^3 (37.0)
Regenerative Filter, back-flush flow	1	Actual test data	62.6×10^3 (9.0)	127×10^3 (18.5)	220×10^3 (32.0)
System Total			549.7×10^3 (79.8)		1882×10^3 (273.2)

were performed, but it was assumed to be between 4.29×10^{-4} m^3/sec (6.8 GPM) and 8.2×10^{-4} m^3/sec (13 GPM). After further development testing, a 6.31×10^{-4} m^3/sec (10 GPM) flow rate was established as the nominal backflush flow rate. The pump was then sized to obtain a maximum pressure head of 1380×10^3 N/m^2 (200 psi) at a flow rate of 6.31×10^{-4} m^3/sec (10 GPM). This was also used as a basis in designing the filter regeneration unit and in the selection of the individual components. It is apparent from this analysis that the quick disconnects and pipe fittings used in the system create the greatest pressure drop. A survey of quick disconnect vendors did not reveal any quick disconnects that had a lower pressure drop. The pipe fittings were increased in size wherever possible to reduce overall pressure drop.

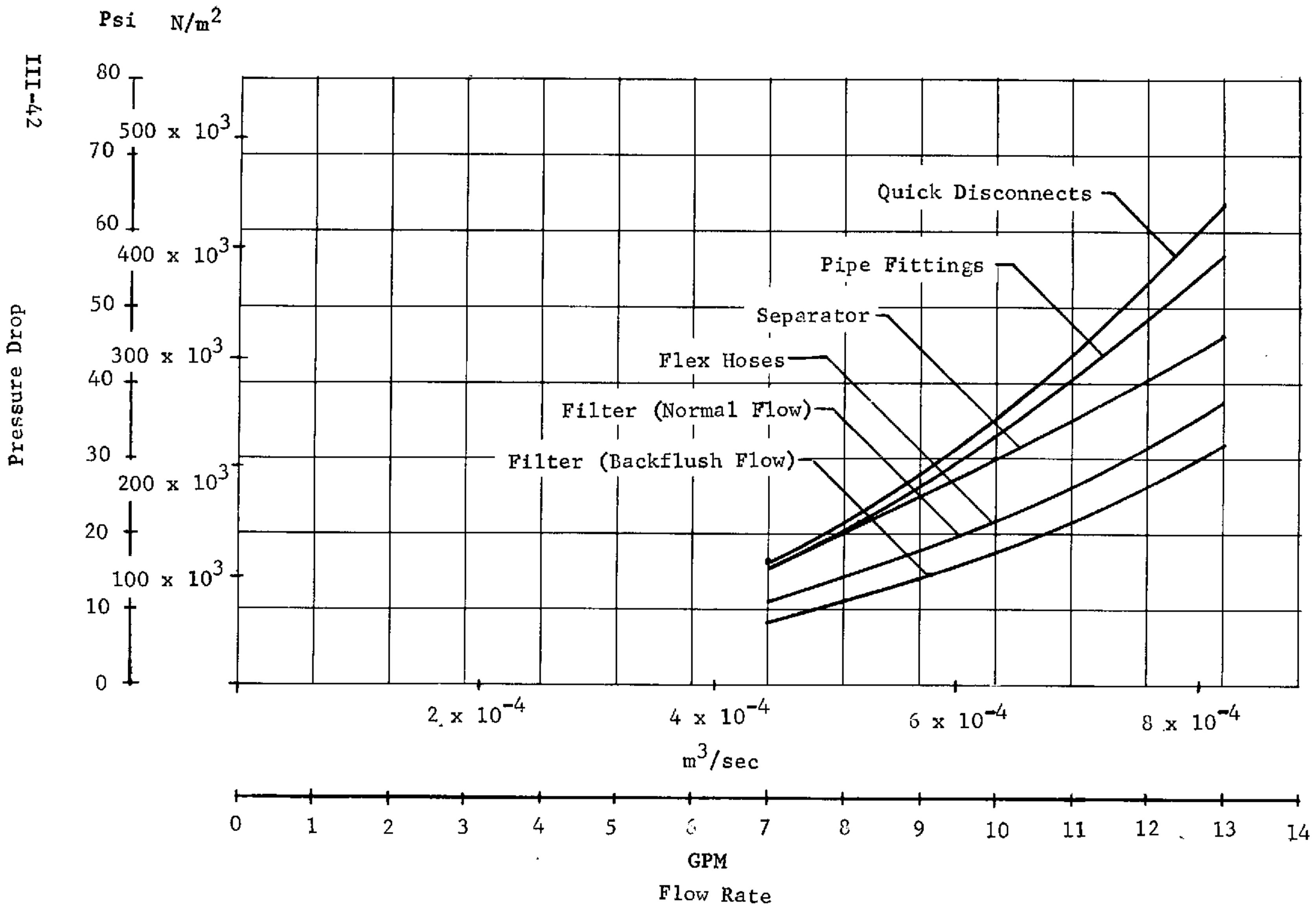


Figure III-25 Component Pressure Drop (Calculated)

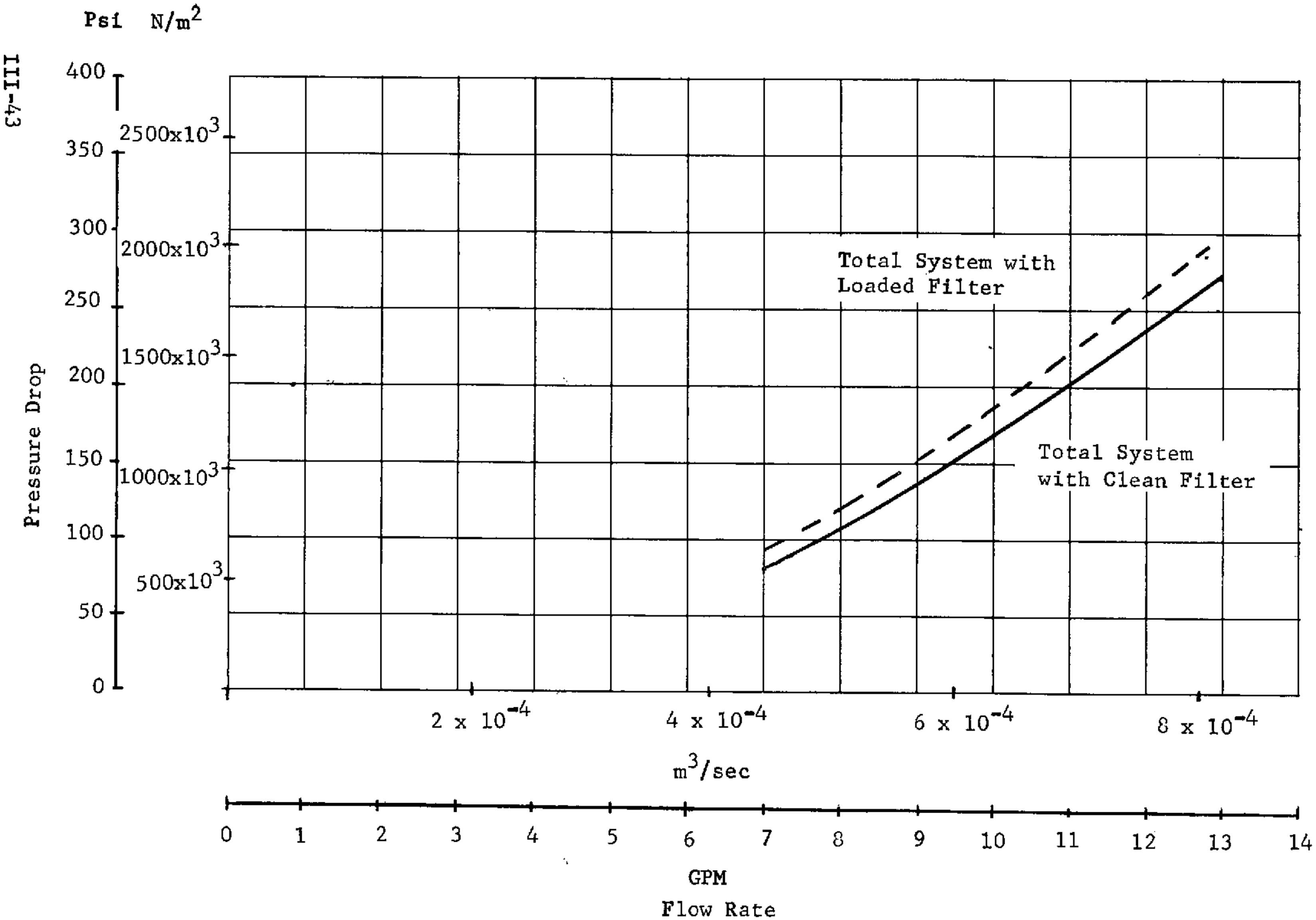


Figure III-26 Regeneration System Pressure Drop (calculated)

The pressure drop for the flex hoses, the two filters, and the separator are relatively fixed and little can be done to reduce them further. If the flex hoses are enlarged the minimum bend radius becomes larger decreasing their mobility. The two filters are sized for the system flow rates already established and the addition of the impingement jet is necessary for optimum regeneration. The separator is also sized at a specific flow rate and the pressure drop cannot be reduced appreciably.

The prototype separator used in the regeneration unit had a higher pressure drop than anticipated as can be seen in Figure III-27. This is due partially to the addition of smaller fittings to the inlet and outlet, but the fittings do not account for all of the increase. Apparently the enlargement of some of the pipe fittings offset the increase in the separator pressure drop since the actual overall system pressure drop has been recorded as 1240×10^3 N/m^2 (180 psid) which is approximately the same value calculated initially.

Typical pressure drop characteristics for the regenerative filters are shown in Figure III-28. These values were obtained by measuring the differential pressure across the pressure tap ports provided on the filter body. The loaded filter curve has been established as a means to determine when the filter requires cleaning. It has been used throughout the testing program and is also acceptable for the secondary filter in the filter regeneration unit.

The backflush flow curve (Figure III-28) is lower than that for a cleaned filter in the normal flow direction. This is due apparently to the restrictions in the filter which must be less in the backflush mode than in the normal flow mode.

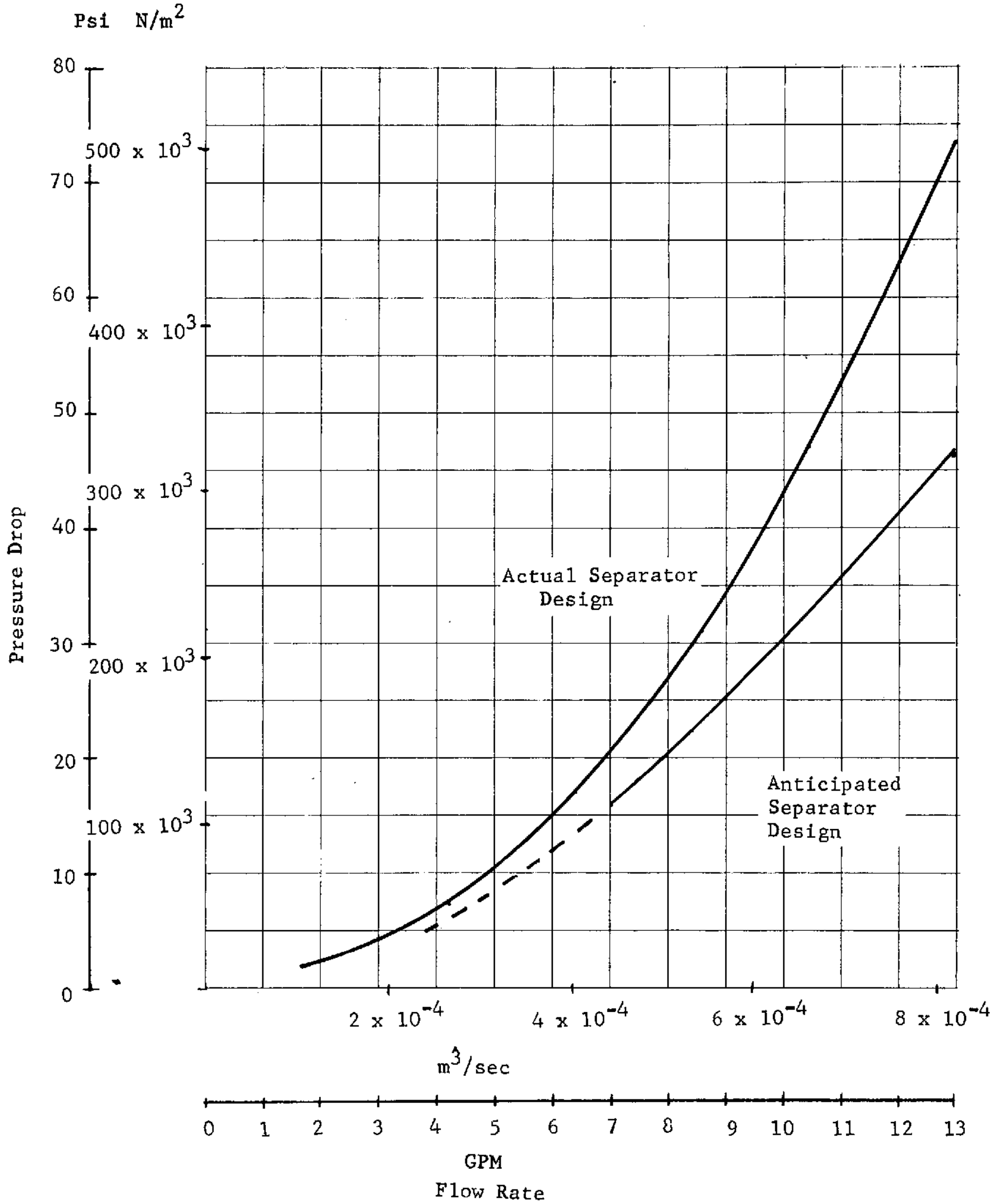


Figure III-27 Separator Pressure Drop

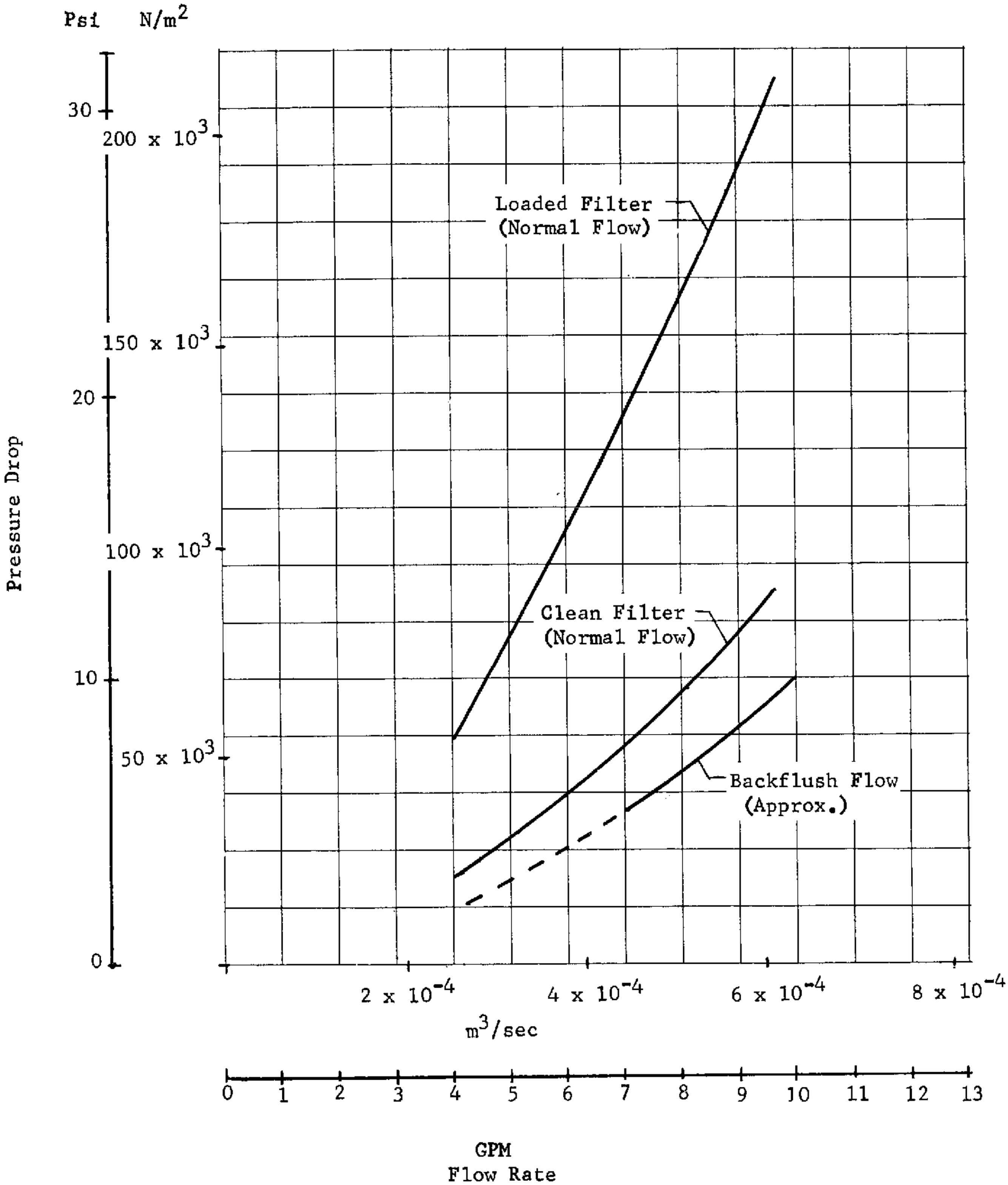


Figure III-28 Regenerative Filter Pressure Drop

F. DEVELOPMENT AND PERFORMANCE TESTING

A test program was conducted, as part of this contract, to fulfill the development requirements and to confirm the functional performance of a regenerative fluid filter system. The tests were performed in two major areas, (1) backflush techniques for cleaning the filter element, and (2) vortex particle separation to collect the contaminant.

All testing was accomplished with water that was filtered on the inlet of the test circuit to remove all particles larger than 2 microns in size. A series of backflush tests were performed to determine the optimum backflush technique, the required flow rate, and the maximum allowable loading pressure drop. A series of separator tests were conducted to determine the optimum flow rate for particle separation versus pressure drop and to develop a particle retention trap suitable for zero-g use.

Performance tests were performed on the separator and filter as separate components, and as a unit, prior to their installation in the prototype filter regeneration unit. These tests were performed in the same open system as the development tests and thus provide a direct comparison with previous data. Following the assembly of the filter regeneration unit, tests were performed on the closed loop system to determine regeneration efficiency, overall efficiency, and regeneration unit performance.

1. Test Contaminants - The filter regeneration development tests were performed using AC coarse road dust as the contaminant. The AC road dust (Figure III-29) is a composite of screened and graded dust particles, primarily quartz, and is a natural road dust from Arizona. The basic composition in each size range is:

Particle Size (microns)	Percent by Weight
0 to 5	12 ± 2
5 to 10	12 ± 3
10 to 20	14 ± 3
20 to 40	23 ± 3
40 to 80	30 ± 3
80 to 200	9 ± 3

The number of particles of a given size per 1.0 mg of road dust is shown in Figure III-30. It may be observed from this data that approximately 60% of the particles are below 40 microns. This is below the 50 micron cutoff specified for the process water, thermal

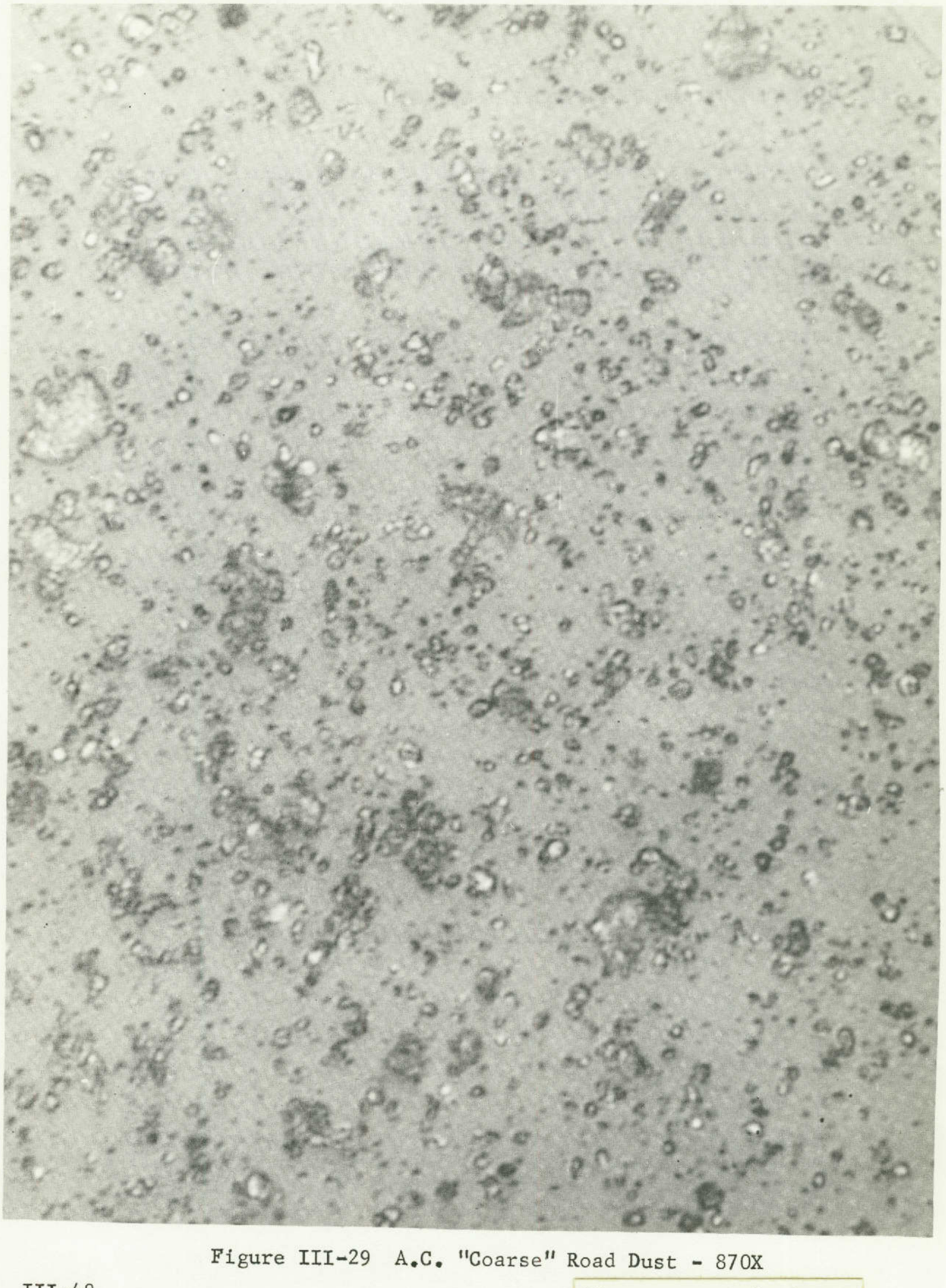


Figure III-29 A.C. "Coarse" Road Dust - 870X

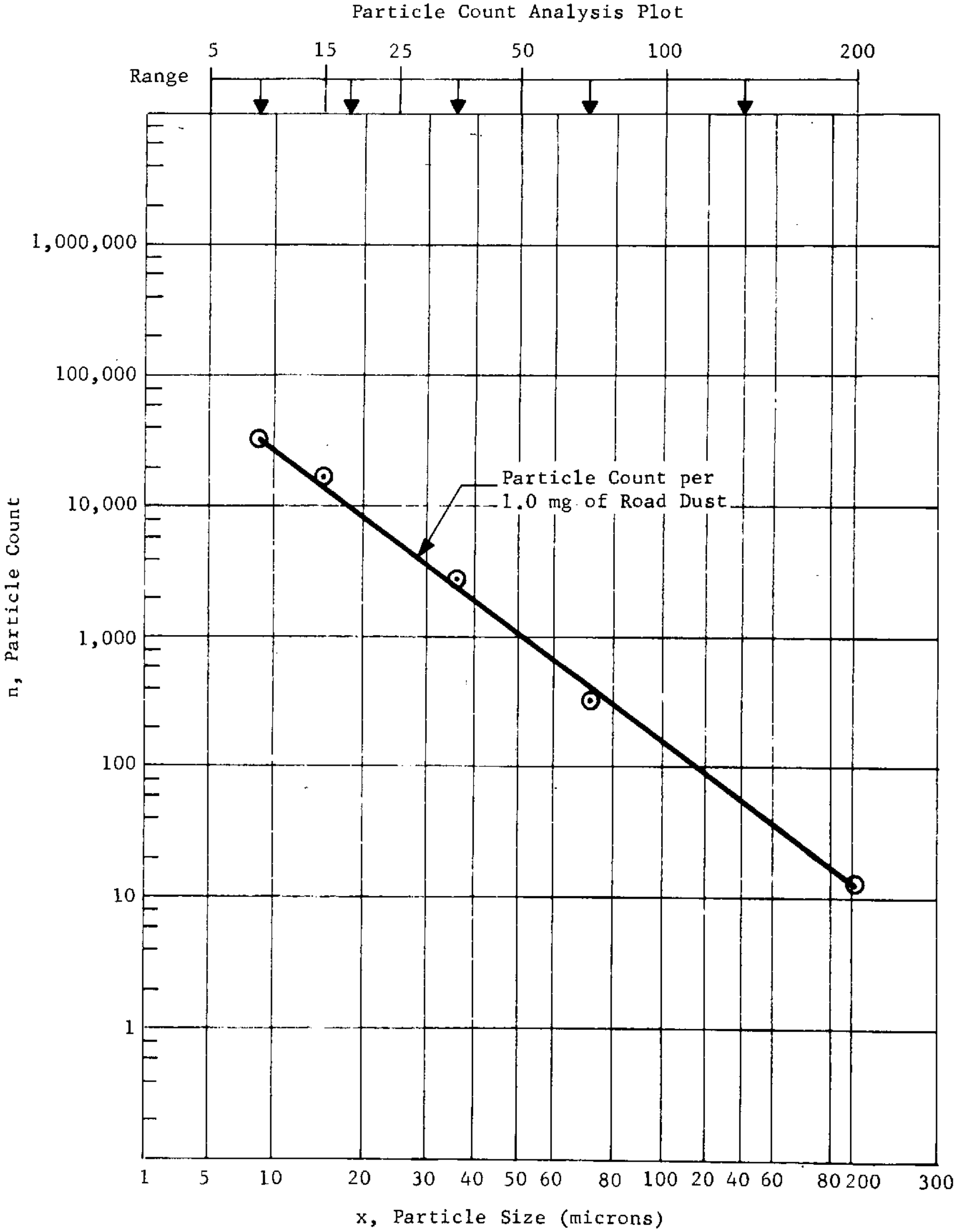


Figure III-30 Particle Count Composition A.C. "Coarse" Road Dust water, and thermal freon systems. The large percentage of particles below the cutoff and the use of test filters with a rating of 10 micron nominal and 25 micron absolute makes the tests extremely conservative.

Because of the large percentage of particles below 40 microns, the road dust was sieved to separate the particles below 43 microns for some of the tests. The method used to separate the contaminant did not remove all of the less-than-43-micron contaminants. The separation process produced an indicated 53.4% of the contaminants greater than 43 micron as compared to 40%, which is the maximum possible. Thus, approximately 25% of the sieved contaminants were actually less than 43 microns. This fact has a significant effect on the indicated test efficiencies and if the contaminants actually were all greater than 43 microns, the test efficiencies would have increased.

For some of the performance tests the filters were also loaded with contaminants obtained from a clothes washer and shower. These were obtained by running the effluent from the washer or shower into a reservoir and from there they were pumped through the filter at predetermined flow rates. It must be noted that the water-contaminant solution contains not only particulate matter but also soap, oils and their reaction products. No analytical analysis was performed on the washer and shower effluent to determine the actual particle range and composition.

2. <u>Error Analysis</u> - At the outset of the tests, the test program was beseiged by a series of small errors that would have ultimately affected the test results if they had not been subsequently resolved. These errors are not uncommon to a contamination test program of this type. The errors are attributed to the fact that the tests involve very small quantities of contamination and any error in resolving quantity injected into the system versus output results in a large error in resultant efficiency. The test procedure required weighing the test contaminant in a pill capsule before injection and also afterward (pill capsule tare weight) to obtain the exact amount of contaminant added. To determine the efficiencies, it was necessary to recover the contaminant which passed through the filter or separator, was backflushed from the filter, or was contained in the filter bowl or separator trap. The contaminants were recovered on 0.45 to 3.0 micron millipore pads which requires a clean and contaminated weight determination to ascertain the weight of the contaminant recovered. The following errors were identified and subsequent discussion details the resolution of these errors.

- Humidity absorption and desorption on the millipore pads.

- Weighing errors.

- Particles trapped in the test system.

- Particles below 0.45 microns.

- Accumulation of small particles in the water supply in a size range of 0.45 microns to 2.0 microns.

Humidity Absorption - When the testing was first started, it was found that it was impossible to accurately weigh the large 293 mm diameter fiber millipore pads used to collect contaminant. Very accurate electron balances were used to weigh the pads, and it was found that the rate of change in weight was too great to compensate for. Rate of change was approximately 2 milligrams per minute with total weight changes as high as 0.3 grams. It was resolved that even though the pads were relatively dry (30% humidity), the absorption and desorption of humidity to the fiber pad was great enough to cause the weighing problem. Even the change between a pad stabilized to the humidity outside the balance and then moved to the humidity inside the balance enclosure would cause a rate of change in weight. The problem was resolved by drying the millipore pads in a vacuum oven at 49°C (120°F) and then enclosing the millipore pads in a plastic bag to preclude absorption of humidity during the weighing process.

Weighing Errors - Very accurate balances are used to weigh the millipore pads, with resolution to $\pm$ .0001 grams. A dry run test was conducted to determine what weighing errors could be incurred during the process. The procedure included the following steps. A clean millipore pad was dryed and weighed, then wetted with water, and again dryed and weighed to complete a typical cycle. Weight change for this test was a minus .0076 grams for a total of four weighings. Operator error could be as much as $\pm$ .001 grams for each weighing.

The first backflush development tests were conducted in three backflush cycles to determine efficiency as a function of flow time. This type of test involved 28 weight determinations. To reduce errors, subsequent tests used only one continuous flow cycle with a reduction in weight determinations to 16 weighings. The number of weighings were further reduced 50% by pairing a pad and bag and weighing that combination with the pad dirty and clean to obtain the net increase.

There is no way to totally eliminate weighing errors and their exact value cannot be determined - only bracketed. The errors were minimized through the instituted program of careful operator procedure and attention to detail.

Trapped Particles - Five contaminant loading tests were conducted with the test filter removed from the test circuit. These tests were conducted to determine if all of the contaminant injected into the system was recovered on the millipore pad. The following data describes the results of those tests.

	Error (grams)	Percent Recovery
Test No. 1	+ .0613	105.25%
Test No. 2	- .0096	99.0%
Test No. 3	- .1650	83.0%
Test No. 4	- .0688	93.7%
Test No. 5	- .0541	95.3%

A root-sum-square of the above errors, excluding Test No. 3, results in a 2.5 percent error. The error in Test No. 3 is so large that it is believed to be an operator error in weighing the initial contaminant injectant loads.

To further enlighten the problem, the entire test system downstream of the contaminant injection port was disassembled down to each fitting, visually inspected, and then flushed with water. The effluent was collected on a millipore pad and then weighed. None of the fittings, valves, or tube sections exhibited any great amounts of contaminant at any one point. The flush produced .0270 grams of contaminant. This is after many grams of contaminant were flowed through the system. The conclusion here was that the system configuration was as "clean" a flow section as was physically possible consistent with the test requirements.

Particles Below 0.45 Microns - One other possibility that was considered in the above problem was that some amount of the AC coarse road dust was in a size range below 0.45 microns, and thus was passing through the millipore pad resulting in a reduction of indicated recovery efficiency. Analytical tests conducted by Martin Marietta on Contract NAS10-5935, "Study of Cleanliness Level Requirements Service Arm Systems - Complex 39" show that the AC coarse road dust contains 12 to 14 percent (by weight) of particles in the size range of 0 to 5 microns. At least 50,000 particles exist that are below 1 micron in size.

A test was conducted where two 0.45 micron millipore pads were placed back-to-back in the holder. The test results were:

Contaminant Injected	1.0596 gms	
Recovered on Top Pad	.9707 gms	= 91.6%
Recovered on Bottom Pad	.0343 gms	= 3.3%
	1.0055 gms	= 94.9%

The above tests indicate that a sizable amount (3.3%) of the particles passed through the first millipore pad. The use of finer micron millipore pads or dual pads incurs very high pressure drops in the test system and is not feasible for the test system being used for the development tests.

Water Supply Contamination (0.45 to 2.0 microns) - The water supply to the test system was prefiltered to 2.0 microns absolute by large depth-type filters. Sub-micronic particles below 2 microns do not affect the test filter or the regeneration cycle, but they do collect on the millipore pad and produce additional contaminant in the regeneration cycle. Two tests were conducted to determine the effects of these very small particles. After thoroughly flushing out the test system, water was flowed through the system into a clean millipore pad. The flow rate was 4.29×10^{-4} m^3/sec (6.8 GPM) for 30 minutes. Test No. 1 produced .0705 grams of contaminant, and Test No. 2 produced .0719 grams; indicating a very constant rate of contaminants in the range of 0.45 to 2.0 microns. This error was accounted for by subtracting a tare of .0712 grams per .772 m^3 of flow for tests using 0.45 micron millipore pads.

Conclusions - The majority of the above errors were resolved, accounted for, or were small and not relevant. The trapped particles is a variable and its resolution would have required an expensive modification to the test system which was not deemed necessary.

Particles passing through the millipore pad would have also required a modification to the test system. Both of these errors were incurred in the development tests and did not affect the performance of the delivered prototype regenerative unit.

The unresolved errors all would tend to raise the indicated regenerative efficiencies, and the results of the development test program would be on the low side.

3. Filter Regeneration Development Tests

Procedure - Filter element backflush tests were conducted to determine and optimize the regenerative efficiencies at various parameters. Figure III-31 shows the schematic of the test system used for these tests. The basic procedure for the backflush tests was to first load a known quantity of AC coarse road dust into the contaminant injection loop, establish a predetermined flow rate into the test filter, and then inject the contaminant. The injections were continued until a predetermined pressure differential was obtained across the filter. The millipore pad was removed and weighed to determine the tare weight of the particles that went through the filter. After the contaminant was loaded, the test filter was backflushed for 30 minutes at a specified flow rate. The particles flushed from the filter element were trapped on the 293 mm, 3.0 micron, millipore pad, thus providing a differential weight needed to determine the cleaning efficiency. Appropriate system pressures and flow rates are recorded during the test.

Filter Elements - Two different filter elements (Figure III-32) were used during the development testing. The first type was an AN6235-4A sintered stainless steel filter element manufactured by Purolator (Part No. 56873) with a rating of 3 micron nominal and 10 micron absolute. This filter element proved to be unsatisfactory for regeneration. Tests indicated that the backflush efficiencies were generally low; less than 89.5%.

The second type of filter was a AN6235-2A Hydraulic Research "421" filter element installed in a specially adapted .019 m (3/4 inch) line size T-type filter designed to reduce pressure drop. The Hydraulic Research 421 element is cleanable and is constructed from a pleated composite stainless steel material. The elements have a rating of 10 microns nominal and 25 microns absolute. This element proved to be considerably better for regeneration.

Development Testing - A total of 22 backflush tests were performed at a variety of flow rates, with 3 micron and 10 micron filter elements, and with and without backflush impingement jets. These tests produced a maximum regeneration efficiency of 100%. An additional five tests were performed but the results were voided because of gross errors in the results.

Nine filter element backflush tests were conducted with the 3 micron sintered filter element to determine regenerative efficiencies with varying parameters. The results of these tests are shown on Table III-6. Regenerative efficiencies varied between 69.6 and 95.7%.

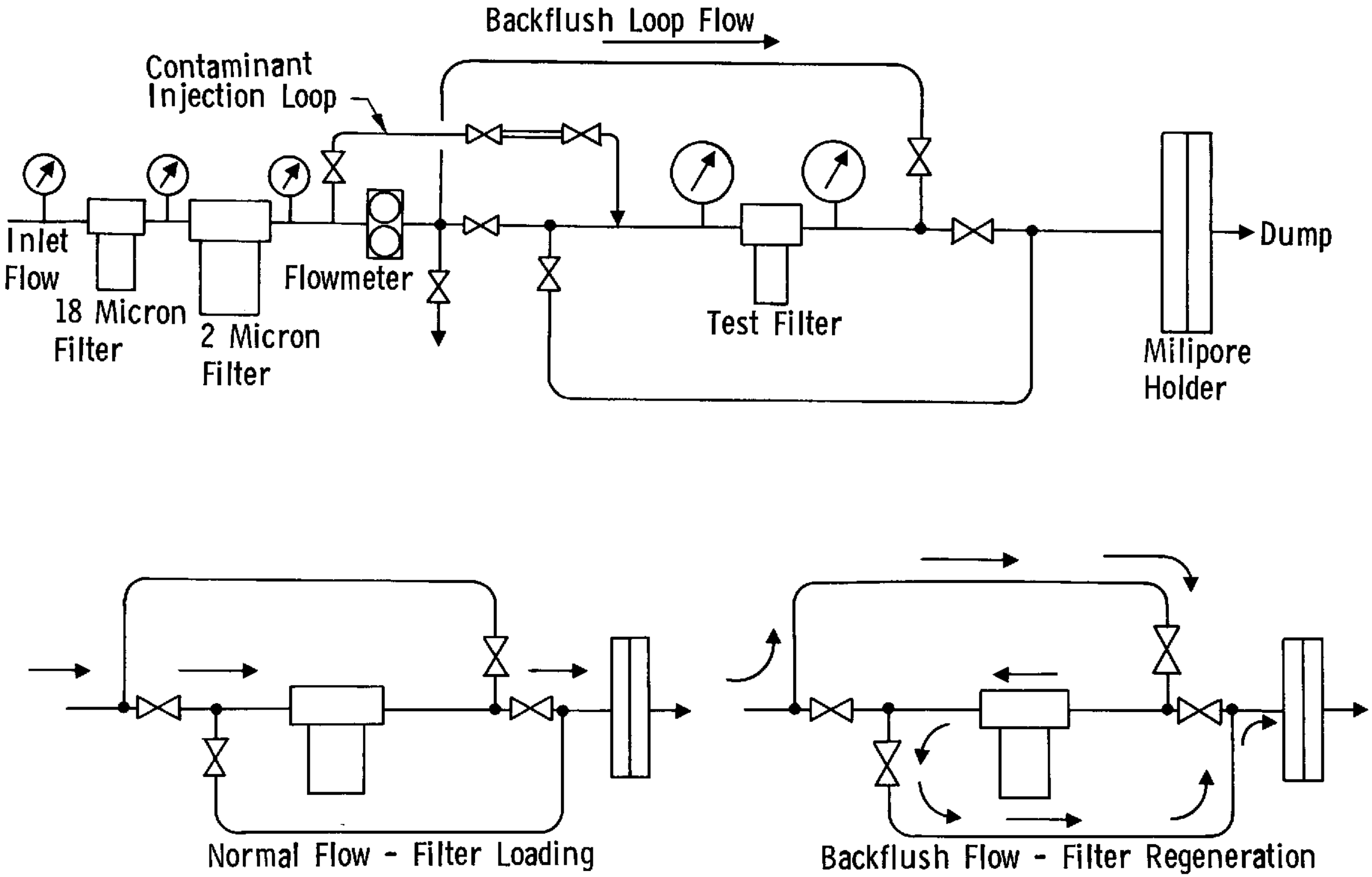


Figure III-31 Filter Regeneration Test Schematic

Figure III-32 Filter Elements Tested

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Table III-6 Backflush Efficiency Tests - Tests 1 thru 9

(1) TEST NUMBER	CONTAMINANT ADDED (grams)			CONTAMINANT REMOVED (grams)				REGENERATIVE EFFICIENCY
	TOTAL ADDED TO SYSTEM	RECOVERED ON MILLIPORE	RETAINED ON FILTER ELEMENT	(2) 30-MINUTE BACKFLUSH	WASHED FROM FILTER BOWL	LESS CORRECTION FACTOR*	NET CONTAMINANT REMOVED	$Eff=\frac{G}{C}$
	A	B	C=A-B	D	E	F	G=D+E-F	
Test 1, Filter 1	1.9938	.0976	1.8962	1.2982	.0935	.0712	1.3205	69.6%
Test 2, Filter 2	2.6960	.2750	2.4210	.9629	.9723	.0712	1.8640	77.0%
Test 3	1.0154	.0879	.9275	.5905	.2361	.0712	.7554	81.4%
Test 4	1.0698	.1231	.9467	.6371	.2703	.0712	.8363	88.3%
Test 5	None	None	None	.0785	N/A	.1040	Zero	0 %
Test 6	1.0391	.2000	.8391	.6488	.0957	.1040	.6405	76.5%
Test 7, Filter 3	.4712	.0763	.3949	.2082	.2123	.0712	.3493	88.5%
Test 8	.2859	.0510	.2349	.1290	.1127	.0712	.1705	72.6%
Test 9	.2588	.0673	.1915	.1261	.1284	.0712	.1833	95.7%

*correction for small particles (.45 to 2.0μ)

(1)Filter element type AN6235-4A, 3 micron nominal

(2)Backflush flow rate from 4.29×10^{-4} to 6.3×10^{-4} m^3/sec (6.8 to 10.0 GPM)

All of the contaminant loadings were conducted at the baseline flow rate of 4.29×10^{-4} m^3/sec (6.8 GPM), the elements were backflushed for 30 minutes each, and the filter housing was disassembled and rinsed into a 3 micron millipore pad at the conclusion of each test.

Test 1 was performed with a backflush flow rate of 4.29×10^{-4} m^3/sec (6.8 GPM) with three different flush cycles for a total of 30.5 minutes flush time. This test was performed to determine the efficiency that could be achieved at the baseline flow rate. The overall corrected efficiency was 68.9 percent. Figure III-33 shows the regenerative efficiency as a function of time. It can be seen that very little contaminant was removed after 15 minutes of backflush. Later tests showed that very high efficiencies could be achieved in 5 minutes or less.

Tests 2 through 6 were performed on Filter No. 2. Tests 2, 3, and 4 were conducted at a backflush flow rate of 4.29×10^{-4} m^3/sec (6.8 GPM) and resulted in efficiencies that ranged from 77.0 to 88.3%. The purpose of these tests were to (1) determine if the cleaning efficiency improved or became worse as a function of cleaning cycles, (2) to see if any degradation occurred in the filter element as a result of repeated cleaning cycles, and (3) determine the effects of cleaning efficiency versus resultant dirt capacity.

These tests did not show any overwhelming evidence that there was any increased efficiency as a function of cleaning cycles, and further that no filter element degradation was evident. These conclusions were further confirmed by later testing.

Figure III-34 shows the dirt capacity for a clean filter and the resultant capacity after successive cleaning cycles. The conclusion reached for the five series of cleaning cycles was that the very small particles initially loaded onto the element became imbedded in the depth of the filter and as a result were not flushed out. These imbedded particles also limit the subsequent dirt capacities, and successive particles form a layer on top of the first small layer. It would appear that these latter particles were essentially flushed out on each cycle since approximately 1.0 grams of dust was loaded onto the element after each backflush. Later testing with larger particles showed a considerably higher capacity thus strengthening this conclusion.

Test No. 5 was conducted at a higher flow rate (6.3×10^{-4} m^3/sec), and with no particulate added to the element, to gauge the effects of a higher flow velocity and also to see if any of the residual particulate, collected during previous tests, could be flushed out.

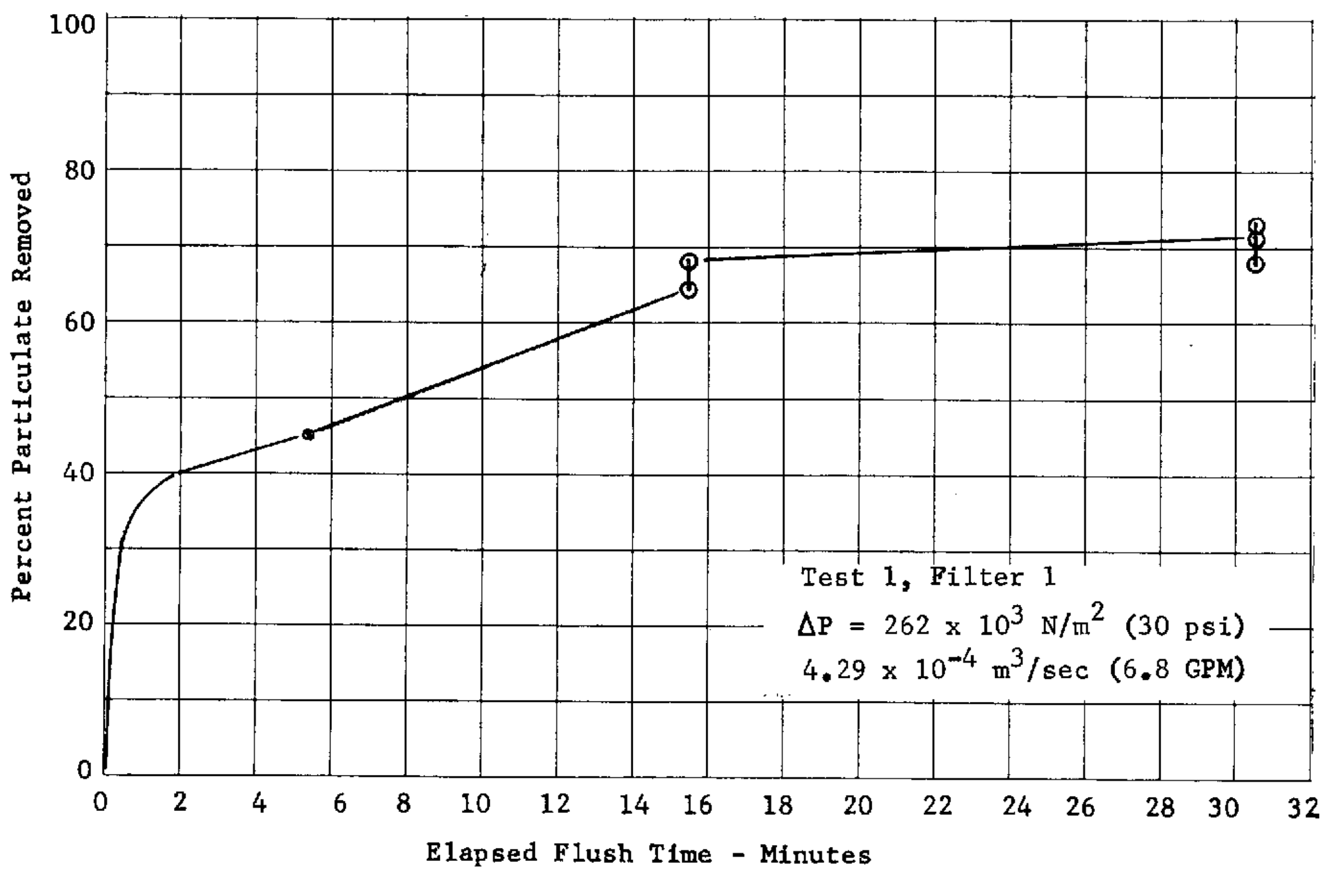


Figure III-33 Regeneration Efficiency

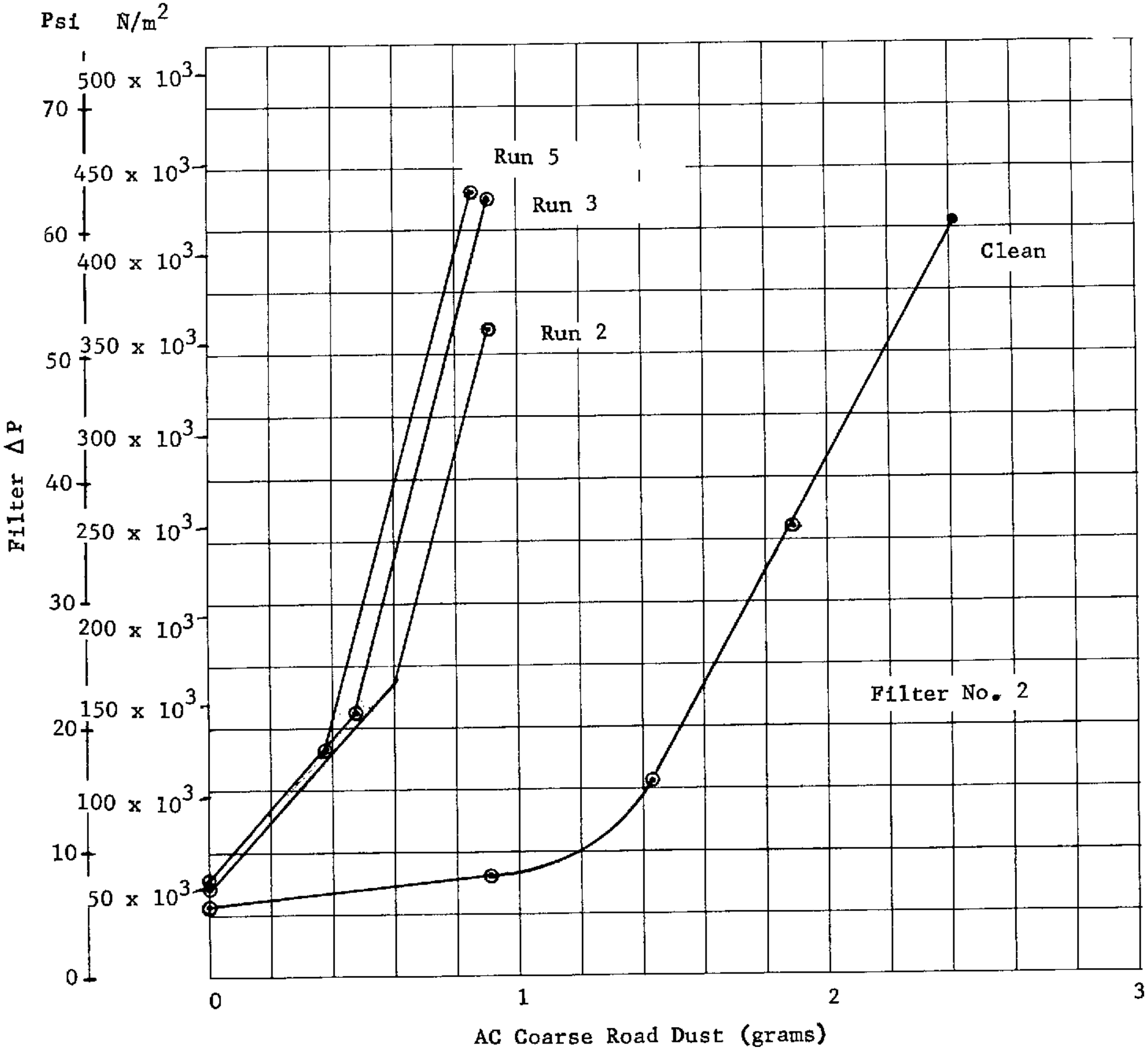


Figure III-34 Dirt Capacity - Backflush Efficiency Runs 2, 3 and 5

After making the tare correction for small particles, the resultant cleaning efficiency was essentially zero.

Test No. 6 on Filter 2 was conducted at a high flow rate (6.30×10^{-4} m^3/sec) to see if the cleaning efficiency was improved over that at 4.29×10^{-4} m^3/sec. No increase in efficiency was noted.

Tests 7 through 9, using filter no. 3, were conducted to determine the effect of contaminant loading cutoff ΔP upon cleaning efficiency. Flow theory and the experience of others indicate that with high pressure drops across the element, particles tend to be extruded farther into the element thus being harder to clean out. Contaminant was loaded onto Filter No. 3 until the pressure drop across the filter element and housing reached approximately 137×10^3 N/m^2 (20 psi), whereas on previous tests, Filter 1 was loaded to 260×10^3 N/m^2 (38 psi) and Filter 2 was loaded up to 431×10^3 N/m^2 (63 psi). The contaminant loading ΔP's were:

Test 7	137×10^3 N/m^2 (20 psi)
Test 8	151×10^3 N/m^2 (22 psi)
Test 9	171×10^3 N/m^2 (25 psi)

Tests 7 through 9 showed the same trends as previous tests whereas the dirt capacity of the element was halved after the first backflush indicating that small particles clogged the inner layers of the element on the first run, and that cleaning efficiency thereafter was very acceptable. Indicated cleaning efficiencies for these tests were higher than previous tests (72.6 to 95.7), however with only 0.2 to 0.4 grams of contaminant being loaded, the element of error becomes much greater leaving some doubt as to the exact validity of the regenerative efficiencies. The indication was encouraging and in the right direction and low ΔP cutoff were used in the remaining tests.

These backflush tests showed that the technique is feasible. The results after the initial backflush were good, but the initial backflush of the filter was unsatisfactory. The initial loading problem probably would not occur if the contaminant sample consisted of larger particles. Tests 1 through 9 were conducted with a AN6235-4A sintered element (3-10 microns) and with straight backflush (no jet) at flow rates of 4.29×10^{-4} to 6.3×10^{-4} m^3/sec (6.8 to 10 GPM).

Additional tests were conducted using three different designs of impingement jets, Figure III-35, which were designed to increase the impingement velocities in order to increase cleaning efficiencies. The first jet (no. 1) was constructed with slots 4.57×10^{-4} m (.018 in.) in width on 1.27×10^{-3} m (.050 in.) centers. Jet no. 2

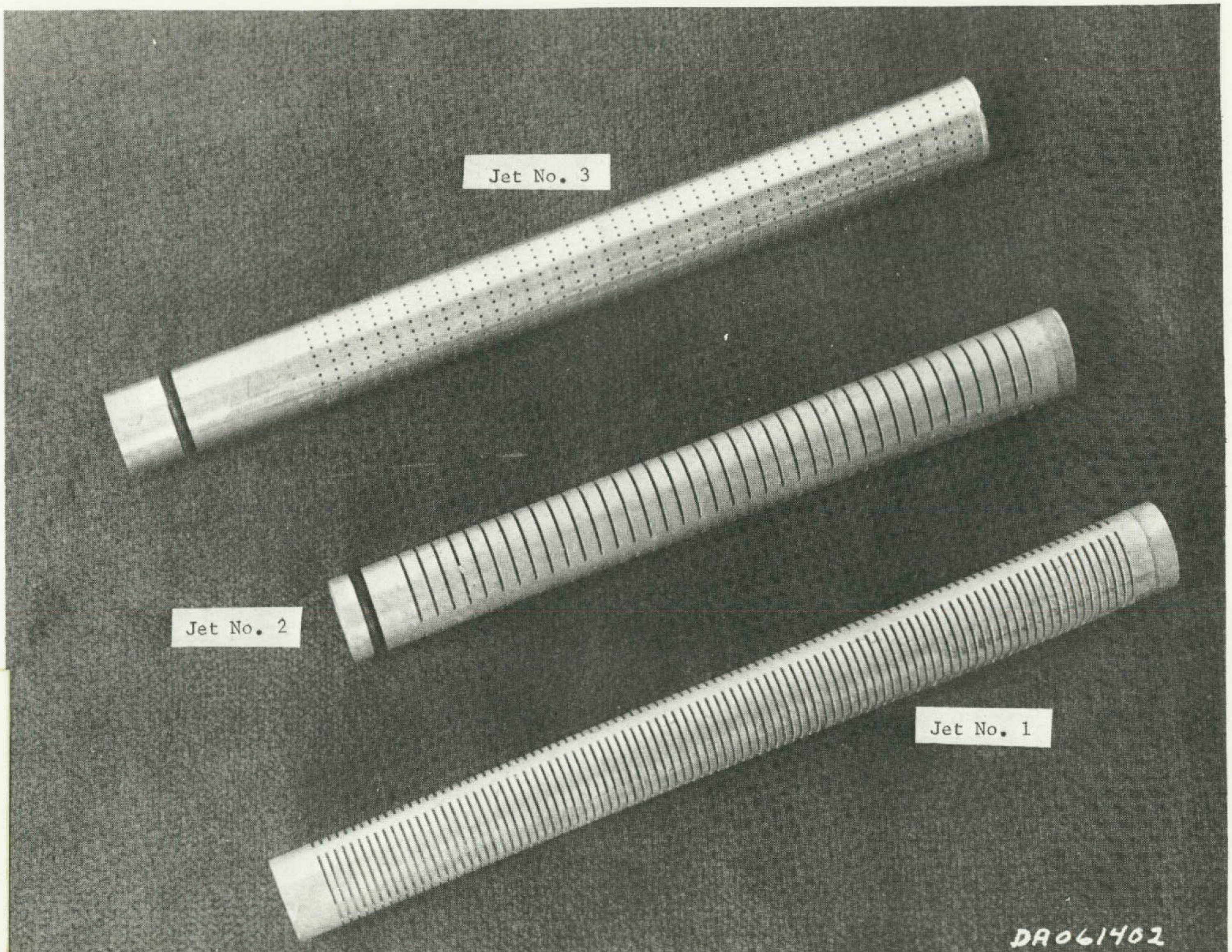


Figure III-35 Impingement Jets

was constructed with the same width slots but on 2.54×10^{-3} m (.100 inch) centers. Jet no. 3 was fabricated having 1148 holes, each with a diameter of 5.08×10^{-4} m (.020 inches). The holes were spaced on centers of 1.42×10^{-3} m x 2.54×10^{-3} m (.056 x .100 inches). The Hydraulic Research filter #421, AN6235-2A, was used for the remainder of the development and performance tests conducted on this program.

The first series of tests were conducted at a flow rate of 4.29×10^{-4} m^3/sec (6.8 GPM) with jet no. 1. The results of the test were voided because of particle leakage across the millipore pad seal and because of a drop in line pressure during the test which resulted in decreasing flow rates. The tests did indicate, however, that the filter was not being cleaned at these velocities and that the jet velocities must be increased.

The second series of tests were conducted on filter element no. 4 and with jet no. 2. The filter was loaded with AC coarse road dust until the pressure drop reached 138×10^3 N/m^2 (20 psi). The tests were conducted with an initial flow rate of 8.52×10^{-4} m^3/sec (13.5 GPM) decreasing to approximately 5.68×10^{-4} m^3/sec (9 GPM) at the end of the 30 minutes backflush run. The calculated vena contracta jet velocity was 3.265 m^3/sec (9.6 ft/sec) at 8.20×10^{-4} m^3/sec (13 GPM). The results of these tests are shown in Table III-7. Regenerative efficiencies varied between 97.0 and 102.4 percent.

The intent of the jet no. 3 design was to reduce the flow area and increase the flow velocity. However, the jet had less "jet force" than the slotted jet no. 2 and produced a velocity impingement that was very light, approaching that of a fogging effect. The first series of tests, Table III-8 and III-9, verified the preliminary indications and the resultant cleaning efficiency proved to be low, 52.7 to 93.5 percent. Although the 93.5% appears high, the loading capacity decreased indicating that it was not thoroughly cleaned. Test no. 13 was conducted at 6.3×10^{-4} m^3/sec (10 GPM), and test no. 14 started at 7.25×10^{-4} m^3/sec (11.5 GPM) decreasing to 5.36×10^{-4} m^3/sec (8.5 GPM).

The second series of tests were conducted with jet no. 2 (slotted jet) to determine if acceptable cleaning efficiencies could be achieved at lower flow rates. Previous tests showed that satisfactory cleaning could be achieved at 8.20×10^{-4} m^3/sec (13 GPM). The target flow rate for these tests was 6.3×10^{-4} m^3/sec (10 GPM).

Cleaning efficiencies were good, 94.4% overall for tests 16 through 19, and the clean pressure drop of the filter was constant at 83×10^3 N/m^2 (12 psi). Test no. 19 was conducted without adding any additional road dust to the element, and plugging the bottom half of the jet to determine if better flow distribution to the top half

Table III-7 Backflush Efficiency Tests - Tests 10 thru 12

(3) TEST NUMBER	CONTAMINANT ADDED (grams)				CONTAMINANT REMOVED (grams)				REGENERATIVE EFFICIENCY
	TOTAL ADDED TO SYSTEM	RECOVERED ON MILLIPORE	LESS CORRECTION FACTOR*	RETAINED ON FILTER ELEMENT	(4) 30-MINUTE BACKFLUSH	WASHED FROM FILTER BOWL	LESS CORRECTION FACTOR*	NET CONTAMINANT REMOVED	$Eff = \frac{H}{D}$
	A	B	C	D=A-B-C	E	F	G	H=E+F-G	
Test 10, Filter 4	1.9902	.3451	(2) .0267	1.6718	1.6830	.0474	(1) .0237 (2) .0801	1.6266	97.3%
Test 11	1.7108	.4588	(2) .0534	1.3054	1.2653	.1254	(2) .0534	1.3373	102.4%
Test 12	1.2677	.3102	(2) .0267	0.9842	0.9465	.0613	(2) .0534	0.9544	97.0%

*(1) Correction for small particles (0.45 to 2.0μ)

(2) Correction for anti-static coating (.0267 gm/pad)

(3) Filter element type AN6235-2A, 10 micron nominal with Jet No. 2

(4) Backflush flow rate of 8.52 x 10^{-4} m^3/sec (13.5 GPM)

Table III-8 Backflush Test Summary - Tests 13 thru 22

TEST NUMBER (1)	JET NO.	FLOW RATE m^3/sec	FLOW RATE (GPM)	CLEANING EFFICIENCY	ΔP AFTER CLEANING N/m^2 (psi)	REMARKS
Test 13, Filter 5	3	6.31×10^{-4}	(10.0)	52.7%	76×10^3 (11.0)	To Test Jet No. 3
Test 14	3	7.25×10^{-4} 5.36×10^{-4}	(11.5 - 8.5)	93.5%	86×10^3 (12.5)	To Test Jet No. 3
Test 15	3	N/A	N/A	N/A	N/A	Contaminant Loading
Test 16	2	6.31×10^{-4} 5.68×10^{-4}	(10.0 - 9.0)	86.8%	83×10^3 (12.0)	Cleaning Tests at 10 GPM
Test 17	2	6.31×10^{-4} 5.17×10^{-4}	(10.0 - 9.0)	91.5%	83×10^3 (12.0)	Cleaning Tests at 10 GPM
Test 18	2	6.31×10^{-4} 6.05×10^{-4}	(10.0 - 9.6)	100.5%	83×10^3 (12.0)	Cleaning Tests at 10 GPM
Test 19	2 - top half	6.31×10^{-4} 4.92×10^{-4}	(10.0 - 7.8)	98.4% overall	86×10^3 (12.5)	Flow Thru Top Half of Jet
Test 20	2	6.31×10^{-4} 6.05×10^{-4}	(10.0 - 9.6)	N/A	83×10^3 (12.0)	Jet Rotated at 15 Minutes
Test 21	2	6.31×10^{-4} 5.74×10^{-4}	(10.0 - 9.1)	N/A	83×10^3 (12.0)	Full Jet - No Rotation
Test 22	2 - top half	6.31×10^{-4} 5.36×10^{-4}	(10.0 - 8.5)	114.5% overall for Tests 8, 9, 10	83×10^3 (12.0)	Flow Thru Top Half of Jet - Rotated at 15 Minutes. 114% Efficiency Equates to 100% Overall for Total of Tests 16 thru 22.

(1) Filter element type AN6235-2A, 10 micron nominal

Table III-9 Backflush Efficiency Tests - Tests 13 thru 22

(1) TEST NUMBER	CONTAMINANT ADDED (grams)				CONTAMINANT REMOVED (grams)				REGENERATIVE EFFICIENCY
	TOTAL ADDED TO SYSTEM	RECOVERED ON MILLIPORE	LESS CORRECTION FACTOR*	RETAINED ON FILTER ELEMENT	(2) 30-MINUTE BACKFLUSH	WASHED FROM FILTER BOWL	LESS CORRECTION FACTOR*	NET CONTAMINANT REMOVED	$Eff = \frac{H}{D}$
	$\bar{A}$	B	C	D=A-B-C	$\bar{E}$	$\bar{F}$	G	$\bar{H}=\bar{E}+\bar{F}-\bar{G}$	
Test 13, Filter 5	2.0166	.2253	-0-	1.7913	.8130	.1347	-0-	.9450	52.7%
Test 14	1.0756	.2345	-0-	0.8411	.7599	.0229	-0-	.7878	93.5%
Test 15	1.0194	.2209	-0-	0.7985					
Test 16	1.5218	.2905	-0-	1.2313	.9720	.0972	-0-	1.0692	86.8%
Test 17	1.0199	.2154	-0-	.8045	.7122	.0236	-0-	.7358	91.5%
Test 18	0.9445	.2059	-0-	.7386	.7234	.0189	-0-	.7423	100.5%
Test 19	-0-	-0-	-0-	-0-	.1359	.0159	-0-	.1518	94.4% overall
Test 20	1.0247	.2079	-0-	.8186	.3808	N/A	-0-	.3808	
Test 21	-0-	-0-	-0-	-0-	.1091	N/A	-0-	.1091	
Test 22	-0-	-0-	-0-	-0-	.1177	.3280	-0-	.4457	114.5%

(1) Filter element type AN6235-2A, 10 micron nominal

(2) Nominal backflush flow rate of 6.31×10^{-4} m^3/sec (10.0 GPM)

of the filter would improve efficiencies. The cleaning efficiency was improved, but this one test was not sufficient to determine if better flow distribution or just 30 minutes of additional flow time produced the effect. Table III-8 summarizes the results of Tests 16 through 19, Table III-9 outlines the detailed test data for the same tests, and Figure III-36 shows the dirt capacity curves.

The third series of tests were conducted to resolve if better flow distribution or additional flow time produced the increased efficiencies noted in Test No. 19. In addition, the jet was not rotated during tests 16 through 19 and it was thought that this may have reduced efficiencies somewhat.

Test 20 was conducted at a nominal flow rate of 6.31×10^{-4} m^3/sec (10 GPM) and the slotted jet was rotated at 15 minutes into the 30-minute backflush. Jet no. 2 was constructed with a dead spot at the point where the slots meet, and in order to correct for the dead spot the filter was rotated 90 degrees half-way through the backflush cycle. This deficiency was corrected in the design of the jet for the deliverable unit. Test 21 was conducted with no additional contaminants added to the system and at a nominal flow rate of 6.31×10^{-4} m^3/sec (10 GPM) to determine the effects of increased flow time. The jet was not rotated during this test.

Test 22 was conducted with the bottom half of the jet plugged to determine the effects of better flow distribution. The jet was rotated 90 degrees at 15 minutes into the 30-minute backflush cycle.

Tests 20 through 22 produced a cleaning efficiency of 114 percent, which indicated that some residual dirt from tests 16 through 19was being cleaned out. Totaling the dirt added versus that removed for tests 16 through 22 revealed that there was a cleaning efficiency of 100% for a total of 7 cleaning cycles. There was no clear indication as to what singular factor (flow distribution, jet rotation, increased flow time) produced the increased efficiency. The rotation of the jet was duplicated in the fabrication of the jet for the prototype unit through alternated and spaced slots to eliminate blind spots.

These tests show that filters may be regenerated by backflushing at a rate of 6.31×10^{-4} m^3/sec (10 GPM) for 30 minutes provided the filter is not loaded to a pressure drop of greater than 150 $\times 10^3$ N/m^2 (22 psi).

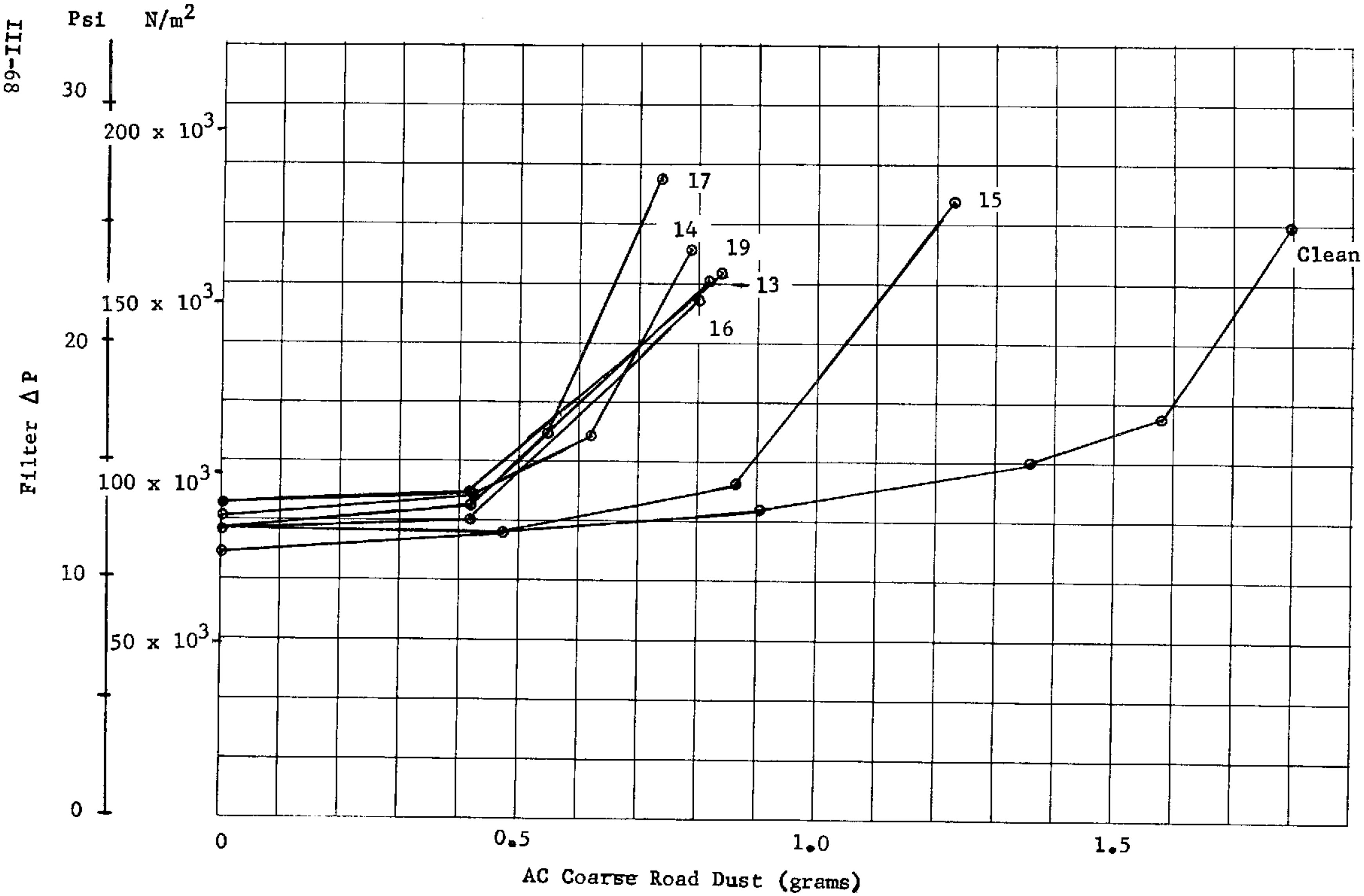


Figure III-36 Dirt Capacity - Backflush Efficiency Runs 13 thru 17, 19

4. Vortex Particle Separator Development Tests - A total of 29 vortex particle separator tests were performed to determine and optimize the separation efficiencies as a function of flow rate and particle trap design. Three types of contaminant were used during these tests, AC road dust, road dust sieved to remove particles greater than 43 microns, and road dust sieved to remove particles less than 43 microns. Two different separators and six different trap configurations were used for these tests.

Procedure - A schematic of the system used for the vortex particle separator development tests is shown in Figure III-37. The procedure for separator testing was to load a known quantity of contaminant into the contaminant injection loop, install a clean and weighed millipore pad in the holder at the system outlet, establish the test flow rate through the separator, and inject the contaminant. The injections were repeated until the pressure drop across the effluent millipore holder became too great, or sufficient contaminants were added to insure a meaningful test. The millipore pad was removed, vacuum dried, and reweighed to obtain the weight of the contaminant that passed through the separator. The contaminants in the separator trap were washed into a millipore pad which was then vacuum dried and reweighed. This provided the weight of the contaminant retained by the separator. From data provided by this procedure, the efficiency of the separator can be determined. During the performance of the test, appropriate pressures and flow rates were determined and recorded.

Test Hardware - The development testing was conducted using two different vortex particle separator configurations and six separator trap configurations. The separator used for the initial testing was a Taylorator type B-2. This is a commercial separator constructed from cast aluminum. The second separator was constructed of plexiglass and of slightly larger dimensions. The plexiglass separator was also used in the filter regeneration unit.

The six separator trap configurations were obtained using four traps with three configurations for one of the traps. The first trap was the commercial trap obtained with the Taylorator separator. This trap design was essentially a cylinder approximately 5.72 cm (2.25 inches) in diameter and 10.2 cm (4.0 inches) long. The remaining traps were designed to prevent re-entrainment of contaminants in zero-g, and were constructed with plexiglass so that their operation could be observed.

The second trap (zero-g trap No. 1) was constructed with a central baffle consisting of four tangential slots approximately .160 cm (.063 inches) wide and 3.8 cm (1.5 inches) long. The trap was

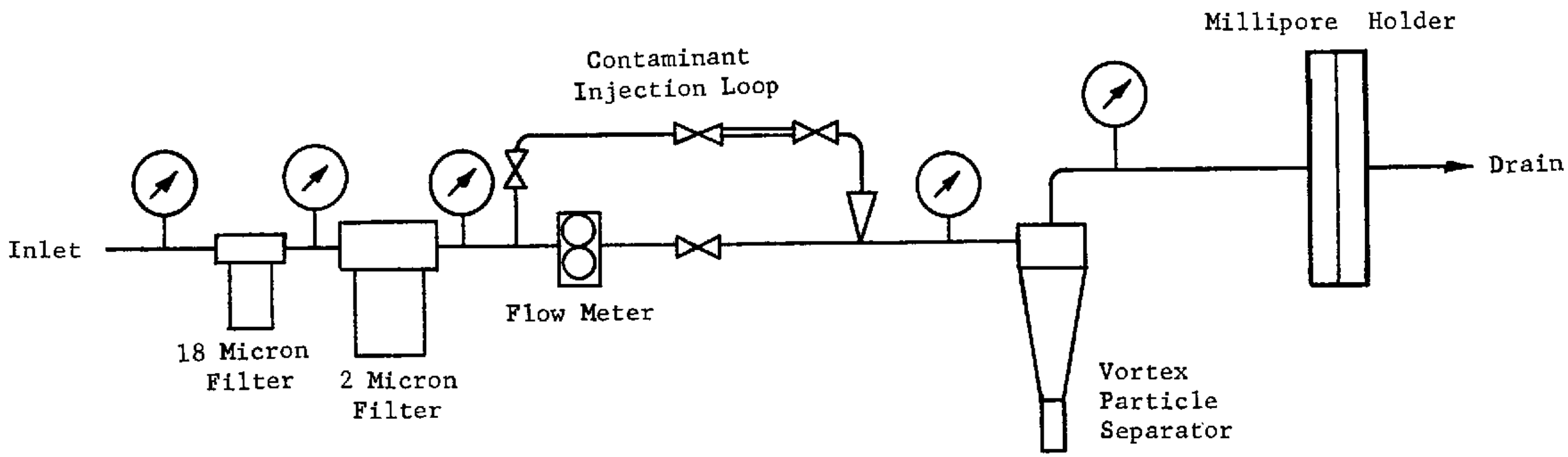


Figure III-37 Vortex Particle Separator Test Schematic tested in three configurations; with four slots open, with one slot open, and with one-half of a slot open.

The third and fourth traps (zero-g traps no. 2 and no. 3) were constructed similar to zero-g trap no. 1 except that they each had only one slot and the central baffle extended about 2.54 cm (1 inch) beyond the slot. Trap no. 2 was fitted with a vane just below the slot to retain the particles in the lower portion of the trap. The three zero-g traps are shown in Figure III-38.

Development Testing - The initial fourteen development tests were performed using the Taylorator separator. The results of these tests are summarized in Table III-10. The flow was continuous during the injection and for one minute after total injection before it was shut off.

The first four tests were conducted using the commercial trap and AC coarse road dust to obtain baseline performance data. The results of these tests were unsatisfactory, showing a maximum of 59% efficiency.

Zero-g trap no. 1 was constructed and used in its three different configurations for the next ten tests. Tests 5 and 6 were conducted in an attempt to determine if zero-g simulation was possible in a one-g environment. Test 5 was conducted with the trap in the normal position (below the separator) and test 6 with the trap inverted (negative one-g). The separator appeared to separate out as many particles in the inverted position as in the normal position, however, the test data was voided because the water drained out of the trap at the conclusion of the test, carrying the trapped contaminant with it. The test did show that zero-g simulation is difficult, if not impossible, to duplicate for this type of test.

In analyzing the results of the previous separator tests, it was evident that the contaminant used for the testing was not compatible with the tests being performed. AC coarse road dust contains a large percentage of particles below 43 microns in size. Since this is not representative of what would exist in any of the systems, as explained in Section III-E Test Contaminants, the road dust was sieved to remove as many particles below 43 microns as possible.

The next eight tests, numbers 7 to 14, were conducted to evaluate the performance of zero-g trap no. 1 in several configurations. The sieved AC road dust was used as the contaminant for these tests. Tests 7 through 10 were conducted with all four slots at the baffle open. As in the previous tests they were performed at four different flow rates from 2.52×10^{-4} m^3/sec (4.0 GPM) to 6.05×10^{-4} m^3/sec (9.6 GPM). The tests show a peak efficiency of 84.4% at 3.35×10^{-4} m^3/sec (5.3 GPM) and a slight drop at the higher flows. It was

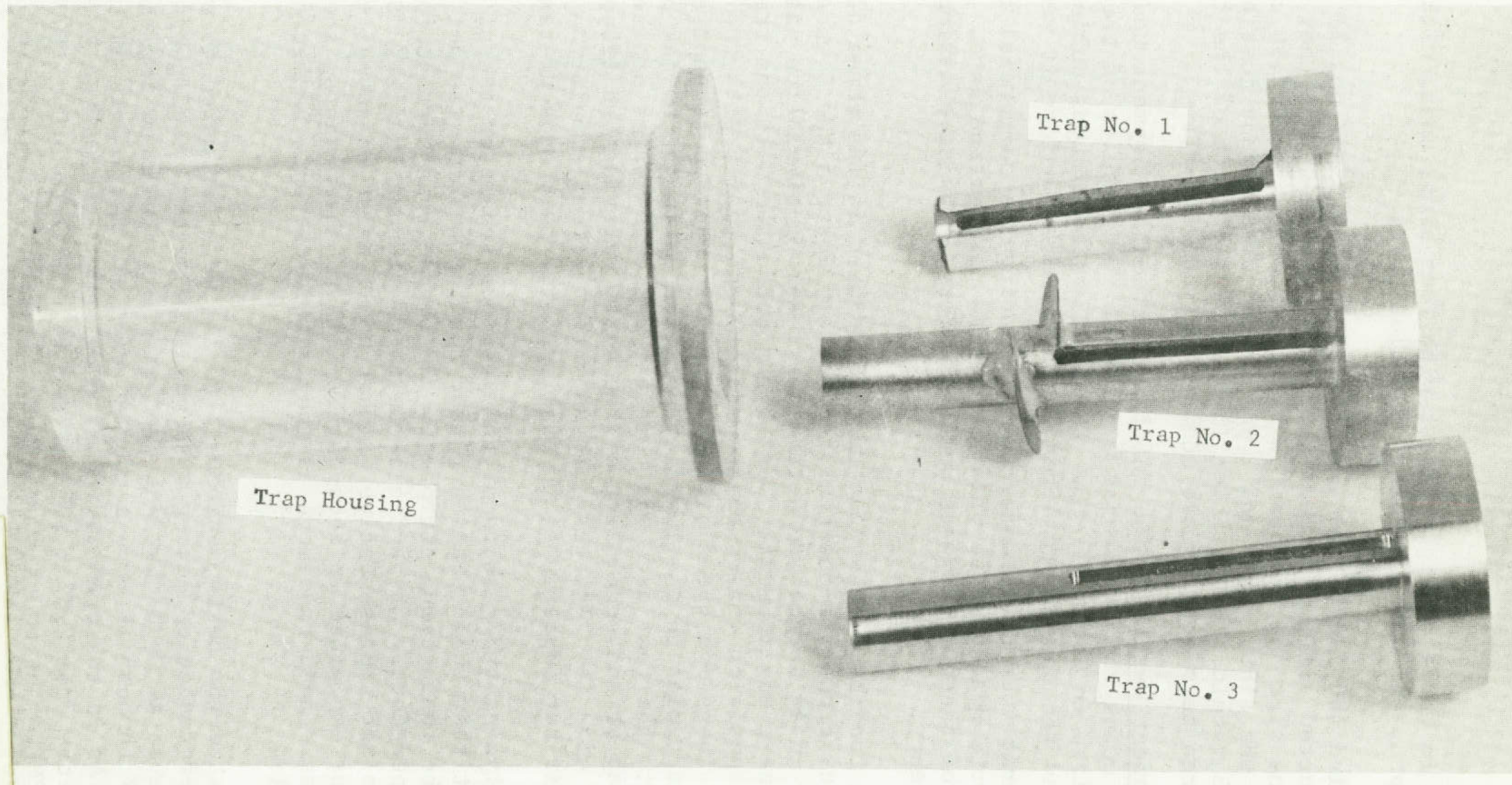


Figure III-38 Zero-G Separator Particle Traps

Table III-10 Particle Separator Efficiency Tests - Tests 1 thru 14

Test No.	Flow Rate $m^3/s \times 10^{-4}$ (GPM)	Contaminant Added (grams)	Separator Efficiency (%)	Separator ΔP $N/m^2 \times 10^3$ (psid)	Test Conditions: Trap	Test Conditions: Contaminant
1	4.29 (6.8)	12.2916	59.1	184-197 (27-29)	Commercial Trap	AC Coarse Road Dust
2	6.05 (9.6)	4.9934	48.6	360-388 (53-57)		
3	3.35 (5.3)	5.0219	51.5	123-180 (18-26.5)		
4	2.52 (4.0)	5.0904	23.7	68-123 (9-18)		
5	4.29 (6.8)	4.9580	63.0	184-197 (27-29)	Zero-G Trap #1 Normal Position	
6	4.29 (6.8)	5.2198	Results Voided	184-197 (27-29)	Zero-G Trap #1 Inverted Position	
7	2.52 (4.0)	4.9686	56.5	69-75 (10-11)	Zero-G Trap #1	AC Coarse Road Dust
8	3.35 (5.3)	4.9728	84.4	114-128 (16.5-18.5)	4 Tangential Slots	Sieved to 43 Micron
9	4.29 (6.8)	4.8801	79.6	200-214 (29-31)		
10	6.05 (9.6)	4.9519	80.6	393-405 (57-58.5)		
11	3.35 (5.3)	4.9433	81.4	124-135 (18-19.5)	Zero-G Trap #1	
12	4.29 (6.8)	4.9182	92.6	203-210 (29.5-30.5)	1 Tangential Slot	
13	3.35 (5.3)	5.1067	82.2	110-169 (16-24.5)	Zero-G Trap #1	
14	4.29 (6.8)	5.0029	90.5	197-214 (28.5-31)	1/2 Tangential Slot	

decided following this test to conduct the remaining tests at the two middle flow rates, 3.35×10^{-4} m^3/sec (5.3 GPM) and 4.29×10^{-4} m^3/sec (6.8 GPM) since the pressure drop at these flow rates was in an acceptable range for the filter regeneration unit and the efficiencies were considerably higher than at the lower flow rate.

During tests 7 through 10, it was observed that particles were being re-entrained through some of the slots in the trap. In an attempt to reduce the turbulence in the trap and thus reduce re-entrainment, three of the four tangential slots were taped off. Tests 11 and 12 were conducted using the trap with only one slot and produced an efficiency of 92.6% at the higher flow rate. This is an increase of 13% over the previous test at the same flow rate.

Tests 13 and 14 were conducted using the third configuration with the upper one-half of the single slot being taped off. These tests showed no significant improvement in efficiency with the decrease in slot area. From these tests it was decided to construct the remaining baffles with one tangential slot.

At this stage of the development program a flow rate of 6.31×10^{-4} m^3/sec (10.0 GPM) was established as the design flow rate for the filter regeneration unit. A separator was sized and constructed from plexiglass based on this flow rate. The plexiglass separator was used for the remaining fifteen tests. The results of these tests are summarized in Table III-11.

The first four of these, tests 15 to 18, provided baseline data for this unit. They were performed using AC coarse dust graded to 43 microns and with zero-g trap no. 2 having one slot and one vane. The tests produced a maximum efficiency of 86.5% with a pressure drop of 379×10^3 N/m^2 (55 psi). This pressure drop was greater than anticipated and a modification was made to the separator overflow tube to increase the inside diameter which reduced the pressure drop to 331×10^3 N/m^2 (47 psi). Later tests using an actual hardware subassembly and respective pressure taps this pressure drop decreased to 290×10^3 N/m^2 (42 psi) as shown in Figure III-27.

The next six tests, number 19 through 24, were conducted to determine efficiencies of the three trap designs. These tests were performed using AC road dust sieved to remove particles greater than 43 microns. It was felt that this contaminant would indicate differences in performance more readily than larger particles, as the smaller particles are harder to separate and retain. These tests indicated minor differences in the efficiencies as a result of trap design. This area of separator design (particle trap) shows promise for increasing the efficiency of a vortex particle separator. Unfortunately there was not sufficient time on this contract to pursue this area of development.

Table III-11 Particle Separator Efficiency Tests - Tests 15 thru 29

Test No.	Flow Rate $m^3/sec \times 10^{-4}$ (GPM)	Contaminant Added (grams)	Separator Efficiency (%)	Separator ΔP $N/m^2 \times 10^3$ (psid)	Test Conditions: Trap	Test Conditions: Contaminant
15	6.31 (10.0)	1.0153	86.5	379 (55)	Zero-G Trap #2 Normal Position, 1 tangential slot	AC Coarse Road Dust Sieved to 44 Microns
16	6.31 (10.0)	1.9819	82.5	379 (55)		
17	6.31 (10.0)	1.9848	84.9	379 (55)		
18	6.31 (10.0)	2.0401	86.5	379 (55)		
19	6.31 (10.0)	1.0710	58.6	331 (47)		AC Coarse Road Dust Sieved to remove particles > 43
20	6.31 (10.0)	1.1135	63.8	331 (47)		
21	6.31 (10.0	2.1353	57.2	331 (47)	Zero-G Trap #1 Normal Position, 1 tangential slot	
22	6.31 (10.0)	2.1122	57.6	331 (47)		
23	6.31 (10.0	2.0339	57.0	331 (47)	Zero-G Trap #3 Normal Position, 1 tangential slot	
24	6.31 (10.0)	1.8981	54.6	331 (47)		
25	6.31 (10.0)	1.2244	79.5	331 (47)		AC Coarse Road Dust Sieved to 44 Microns
26	6 31 (10.0)	1.1904	91.6	331 (47)		
27	6.31 (10.0)	1.2029	86.7	331 (47)		
28	6.31 (10.0)	2.1161	88.2	331 (47)		
29	6.31 (10.0)	2.2416	86.6	331 (47)		

The remaining five tests, number 25 through 29, were performed to determine the efficiency of the previously modified separator overflow tube. The tests were performed using trap design number 3 and AC coarse road dust sieved to 43 microns. These tests produced a maximum efficiency of 91.6%. This final configuration was selected for use in the filter regeneration unit.

5. Performance Testing - The performance tests of the hardware for the filter regeneration unit were conducted in four basic areas: (1) component verification tests-filter regeneration, (2) component verification tests-separator, (3) filter-separator subassembly tests-open loop, (4) filter regeneration unit. A total of twenty tests were performed in these areas.

Component Verification Test-Filter Regeneration - A total of six performance runs were conducted to determine the regeneration efficiency of the modified filter housing assembly used in the filter regeneration unit. These tests were performed to provide reference data to compare the development test data to the filter regeneration unit performance. The test results are summarized in Table III-12.

The first three tests, performance tests 1 to 3, were performed using the modified filter housing with backflush impingement jet number 2 and a Hydraulic Research Filter. The jet was rotated following 15 minutes of backflushing. The tests were performed using AC coarse road dust, at a loading flow rate of 4.29×10^{-4} m^3/sec (6.8 GPM), and a backflush flow rate of 6.31×10^{-4} m^3/sec (10.0 GPM). The procedure was identical to that of the development tests allowing a direct comparison with these tests. These three tests provided regeneration efficiencies of 99.0%, 102.3%, and 98.7% with an average of 100%. The contaminant loading curves are shown in Figure III-39.

The next two tests, numbers 4 and 5, were performed using washing machine effluent as the contaminant. These filters were loaded to a pressure differential of approximately 207×10^3 N/m^2 (30 psi) as measured across the pressure taps. This is actually a higher pressure reading than would have been measured at the taps used in the development testing. The filter became loaded almost immediately in both of the tests. As indicated in Table III-12, the net contaminant recovered in the tests was 0.3725 grams and 0.2325 grams. This is an average loading of 0.3025 grams per test. The low loading figures plus the speed with which the filters clogged indicate that some property of the wash water, possibly the type of detergent caused the rapid loading.

Table III-12 Backflush Performance Tests - Tests 1 thru 6

(1) TEST NUMBER	CONTAMINANT ADDED				CONTAMINANT REMOVED				REGENERATIVE EFFICIENCY
	TOTAL ADDED TO SYSTEM	RECOVERED ON MILLIPORE	LESS CORRECTION FACTOR*	RETAINED ON FILTER ELEMENT	(2) 30-MINUTE BACKFLUSH	WASHED FROM FILTER BOWL	LESS CORRECTION FACTOR*	NET CONTAMINANT REMOVED	$Eff = \frac{H}{D}$
	A	B	C	D=A-B-C	E	F	G	H=E+F-G	
Test 1	.9995	.2353	-0-	.7642	.6147	.1413	-0-	.7560	99.0%
Test 2	1.0368	.1774	-0-	.8594	.7275	.1519	-0-	.8794	102.3%
Test 3	1.0159	.1835	-0-	.8324	.6743	.1479	-0-	.8212	98.7%
Test 4	N/A	N/A	-0-	N/A	.2031	.1504	-0-	.3725	N/A
Test 5	N/A	N/A	-0-	N/A	.2142	.0183	-0-	.2325	N/A
Test 6	See Test 13 on Table III-14				See Test 13 on Table III-14				

(1) Filter element type AN6235-2A, 10 micron nominal

(2) Backflush flow rate of 6.31×10^{-4} m^3/sec (10.0 GPM)

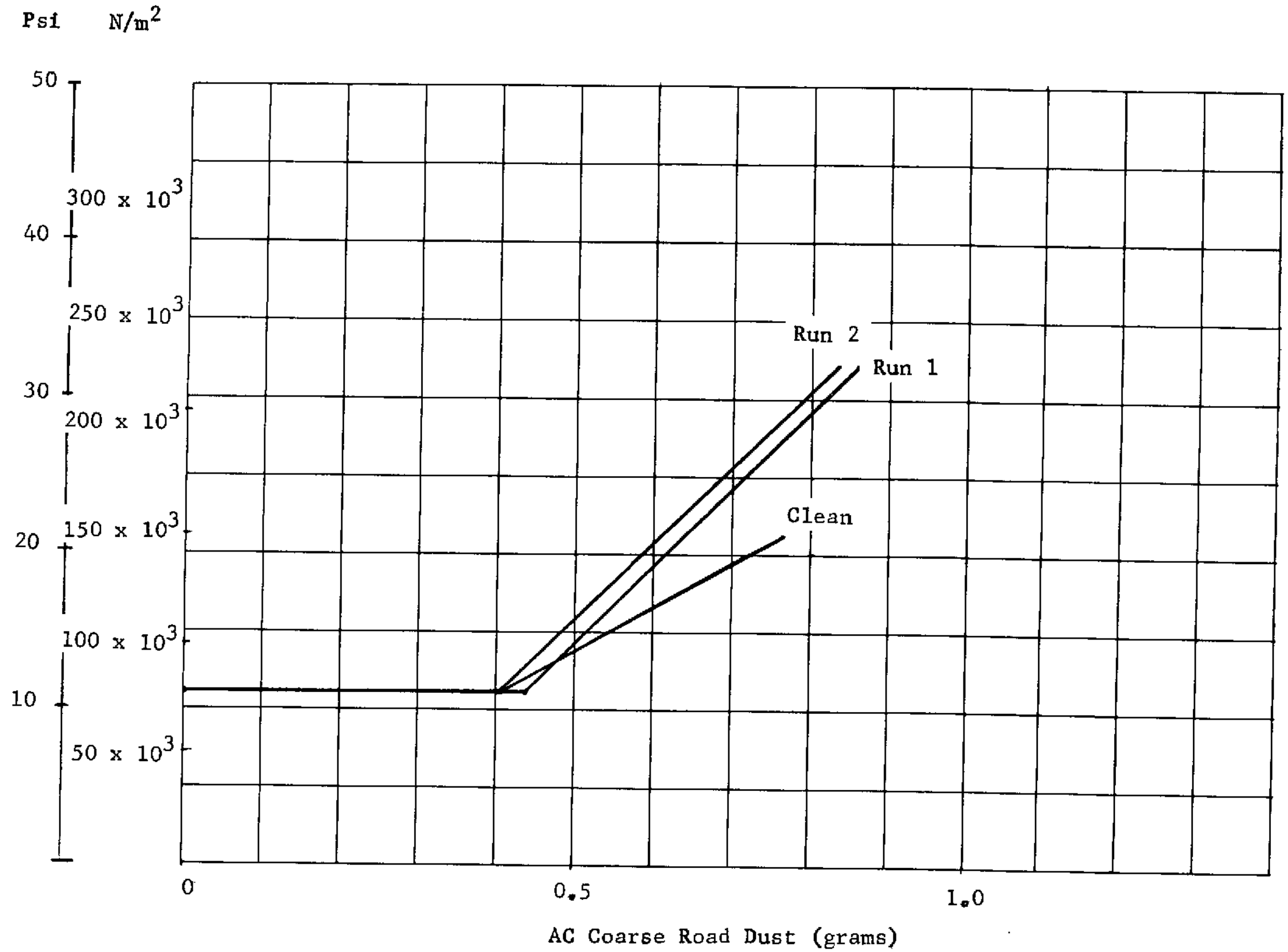


Figure III-39 Dirt Capacity - Backflush Performance Runs 1 and 2

The sixth filter backflush test was run in conjunction with the filter-separator subassembly-open loop tests and will be reported with those as performance test number 13 (see Table III-14).

Component Verification Tests-Separator - A total of four separator runs were performed to establish the efficiency of the final configuration of the plexiglass separator. These tests were performed using the same test system and procedure as used in the development testing. The tests were conducted at a flow rate of 6.31×10^{-4} m^3/sec (10.0 GPM). The maximum separator efficiency was 91.6%, and the average was 88.2% (see Table III-13).

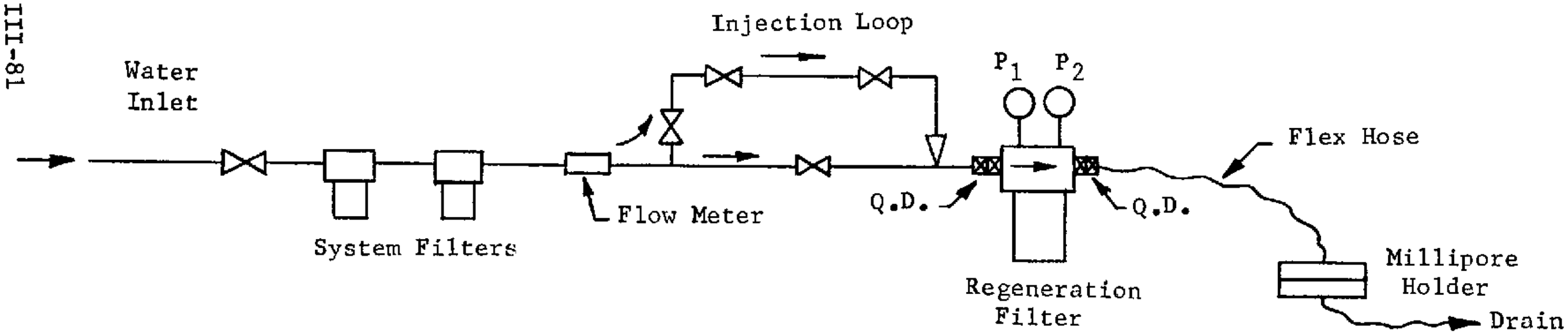
Filter-Separator Subassembly Test-Open Loop - Three tests were conducted using the filter and separator in combination. The tests were performed by loading the filter in almost the same method as used in the previous tests. For these tests the pressure readings were taken from the taps on the filter itself. This reduced the indicated pressure drop by eliminating some of the losses associated with the filter housing. However, since there has always been a certain amount of fluctuation in the loaded pressure differential, the total contaminants loaded are essentially the same. After loading the filter, it is connected upstream of the separator in the backflush direction. A millipore pad and holder were installed downstream of the separator, trapping all effluent. The schematic of this system is shown in Figure III-40.

The subassembly tests were conducted using backflush impingement jet number 4 at a flow rate of 6.31×10^{-4} m^3/sec (10.0 GPM) for a duration of 30 minutes. The contaminant used for the first two tests, performance tests 10 and 11, was AC coarse road dust. The third test, performance test 12, used road dust sieved to 43 microns for the reasons mentioned in Section III-E, Test Contaminants. A fourth test, performance test 13, was a straight backflush test using the same procedure as previous backflush tests, and was performed as a basis of comparison for performance test number 12. The results of these tests are summarized in Table III-14 and the dirt capacity curves are shown in Figure III-41.

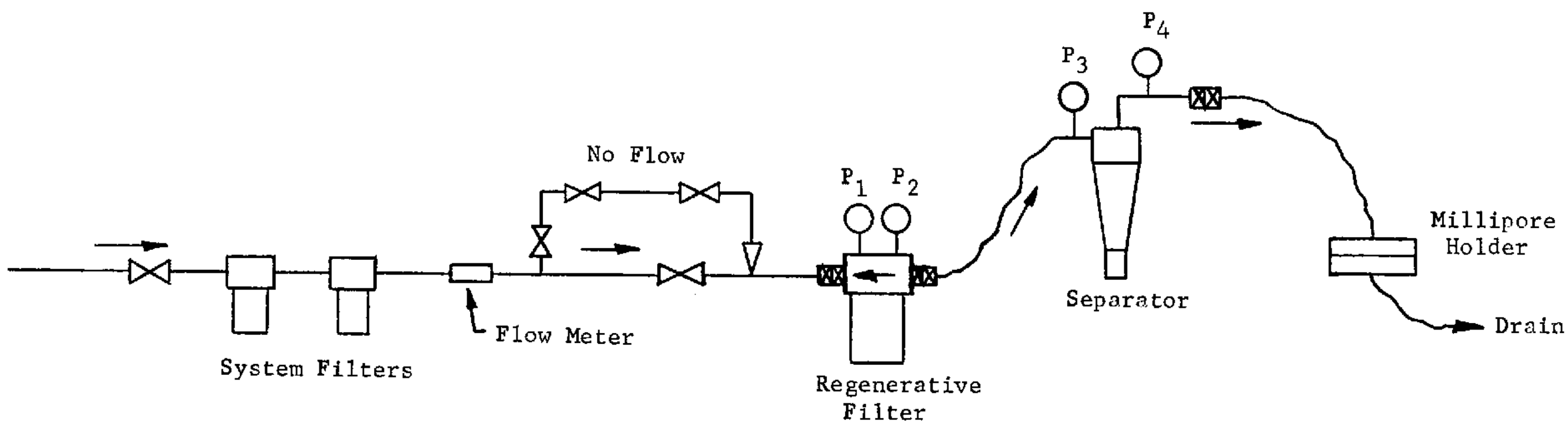
The two tests conducted with AC road dust, tests 10 and 11, showed regeneration efficiencies of 86.5 and 98.8 percent and separator efficiencies of 67.0 and 73.5 percent. There is some question as to the validity of test 11 because an efficiency of 98.8% was obtained the first 10 minutes, and the final efficiency for 30 minutes total backflush was 121.0%. This was assumed to be testing errors. Tests 12 and 13 were conducted with contaminants believed to be more representative of that found in a fluid system which resulted in regeneration efficiencies of 86.5 and 102.1 percent respectively with a separator efficiency of 85.5 percent.

Table III-13 Particle Separator Performance Tests - Tests 6 thru 9

Test No.	Flow Rate $m^3/sec \times 10^{-4}$ (GPM)	Contaminant Added (grams)	Separator Efficiency (%)	Separator ΔP $N/m^2 \times 10^3$ (psid)	Test Conditions	
					Trap	Contaminant
6	6.31 (10.0)	1.1904	91.6	331 (47)	Zero-G Trap #3 Normal Position, 1 tangential slot	AC Coarse Road Dust Sieved to 44 Microns
7	6.31 (10.0)	1.2029	86.7	331 (47)		
8	6.31 (10.0)	2.1161	88.2	331 (47)		
9	6.31 (10.0)	2.2416	86.6	331 (47)		



LOADING MODE



BACKFLUSH MODE

Figure III-40 Filter-Separator Performance Test Schematic

Table III-14 Filter-Separator Subassembly Performance Tests - Tests 10 thru 13

(1) Test No.	CONTAMINANT ADDED (grams)				CONTAMINANT RECOVERED (grams)				EFFICIENCY	
	Total Added to System	Recovered on Millipore	Retained on Filter Element (2)	Size	Separator Trap	Wash from Filter Bowl	Millipore Pad	Net Contaminant Recovered	Separator	Regeneration
	A	B	C = A-B		D	E	F	G=D+E+F	$Eff=\frac{D}{D+F}$	$Eff=\frac{G}{C}$
10	1.3641	.2484	1.1157	AC Coarse Road Dust	0.5123	0.2068	0.2532	.9723	67.0	86.5
11	.9420	.2037	.7383	AC Coarse Road Dust	0.4608	0.1028	0.1662	.7298	73.5	98.8
12	3.6426	.2259	3.4167	AC Coarse Road Dust Sieved to 43 Microns	1.4675	1.2347	0.2507	2.9529	85.5	86.5
13	3.2009	.2596	2.9413	AC Coarse Road Dust Sieved to 43 Microns	N/A	1.2547	1.7439	2.9986	N/A	102.1

(1) Backflush flow rate of 6.31×10^{-4} m^3/sec (10.0 GPM) for 30 minutes
(2) Filter element type AN6235-2A, 10 micron nominal

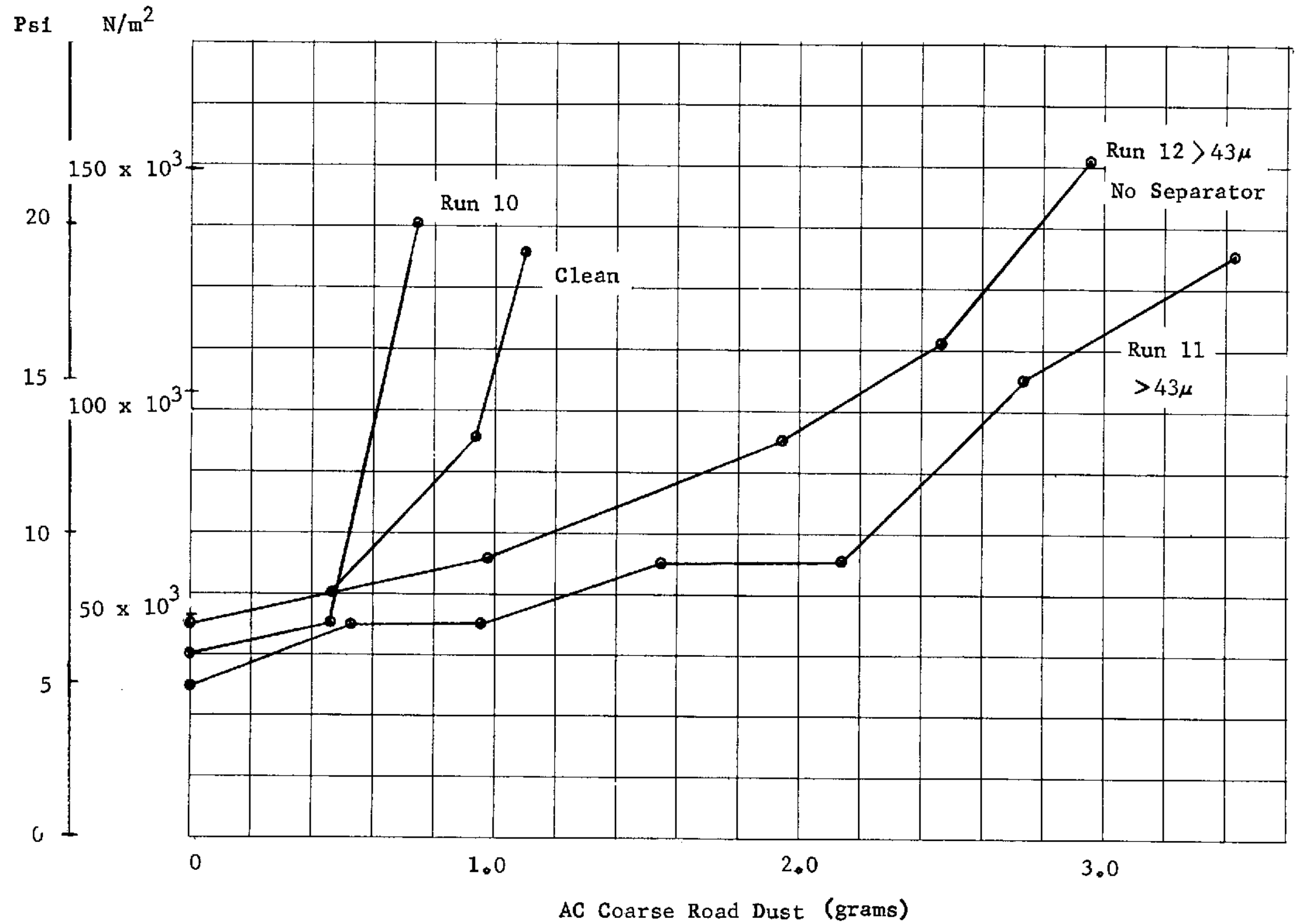


Figure III-41 Dirt Capacity - Backflush Performance Runs 10 thru 12

By observing the separator during the backflush operation, it was noted that the cleaning seemed to occur in the first few moments of operation. Because of this it was decided to operate the filter regeneration unit for only five minutes to determine if acceptable efficiencies could be obtained.

Filter Regeneration Unit-Assembly Tests - A total of seven performance tests were conducted on the filter regeneration unit to determine the overall efficiency. Four of the tests used AC road dust graded to 43 microns as the contaminant. The remaining three tests were conducted using the effluent from a clothes washer and a whole body shower.

Four filter regeneration unit performance tests, using AC road dust, were conducted at a nominal backflush flow rate of 6.31×10^{-4} m^3/sec (10.0 GPM) for a duration of 5 minutes. The filters were loaded to a nominal 138×10^3 N/m^2 (20 psi) at a flow rate of 4.29×10^{-4} m^3/sec (6.8 GPM).

The procedure for loading the filters was identical to that used for the previous filter backflush tests. Following loading, the filter was installed in the filter regeneration unit and regenerated for five minutes. During regeneration, system pressure and the differential pressures of the separator and filters were noted and recorded. The unit flow rate was determined from the pressure differential on the separator. The results of these tests are summarized in Table III-15 and the loading curves are shown in Figure III-42. The dis-continuity of the "clean" curve can be attributed to the readability and accuracy of the gages.

These four tests produced total unit efficiencies of 92.0 and 95.5 percent with an average of 93.8 percent. The results show that the filter is effectively cleaned with a five-minute backflush cycle. It should be noted that these efficiencies are better than those obtained in the open loop system. This indicates that the pulsations from the positive displacement piston pump enhance the backflush cleaning ability.

The secondary filter was backflushed into a millipore pad at the completion of the four regeneration tests, and 0.0861 grams of contaminant were collected. The pressure drop versus flow rate characteristics were determined before the regeneration runs, after the four regeneration runs, and after backflushing. These curves are shown in Figure III-43. The pressure drop in a clean condition, and after regeneration, are essentially the same showing that the filter was returned to its original characteristics. The pressure drop at various flow rates was measured to minimize experimental error and because pressure change

Table III-15 Filter Regeneration Unit Performance Tests - Tests 14 thru 17

(1) Test No.	CONTAMINANT ADDED (grams) Total Added to System	Recovered on Millipore (2)	Retained on Filter Element	CONTAMINANT RECOVERED (grams) Separator Trap	Washed from Filter Bowl	Net Contaminant Recovered	System Flow Rate $x10^{-4}$ m^3/sec (GPM)	Regeneration Efficiency
	A	B	C = A-B	D	E	F = D+E		$Eff=\frac{F}{C}$
14	4.0329	0.2986	3.7343	0.5662	2.8645	3.4307	5.17-5.55 (8.2-8.8)	92%
15	3.5576	0.2360	3.3216	0.9477	2.2339	3.1816	5.43-5.80 (8.6-9.2)	96%
16	3.0262	0.1756	2.8506	0.7750	1.8345	2.6095	5.68-6.64 (9-10.5)	92%
17	3.6216	0.2181	3.4035	1.2741	1.9745	3.2486	6.75-6.95 (10.7-11)	95.5%

(1) Backflush flow cycle for 5 minutes duration

(2) Filter element type AN6235-2A, 10 micron nominal

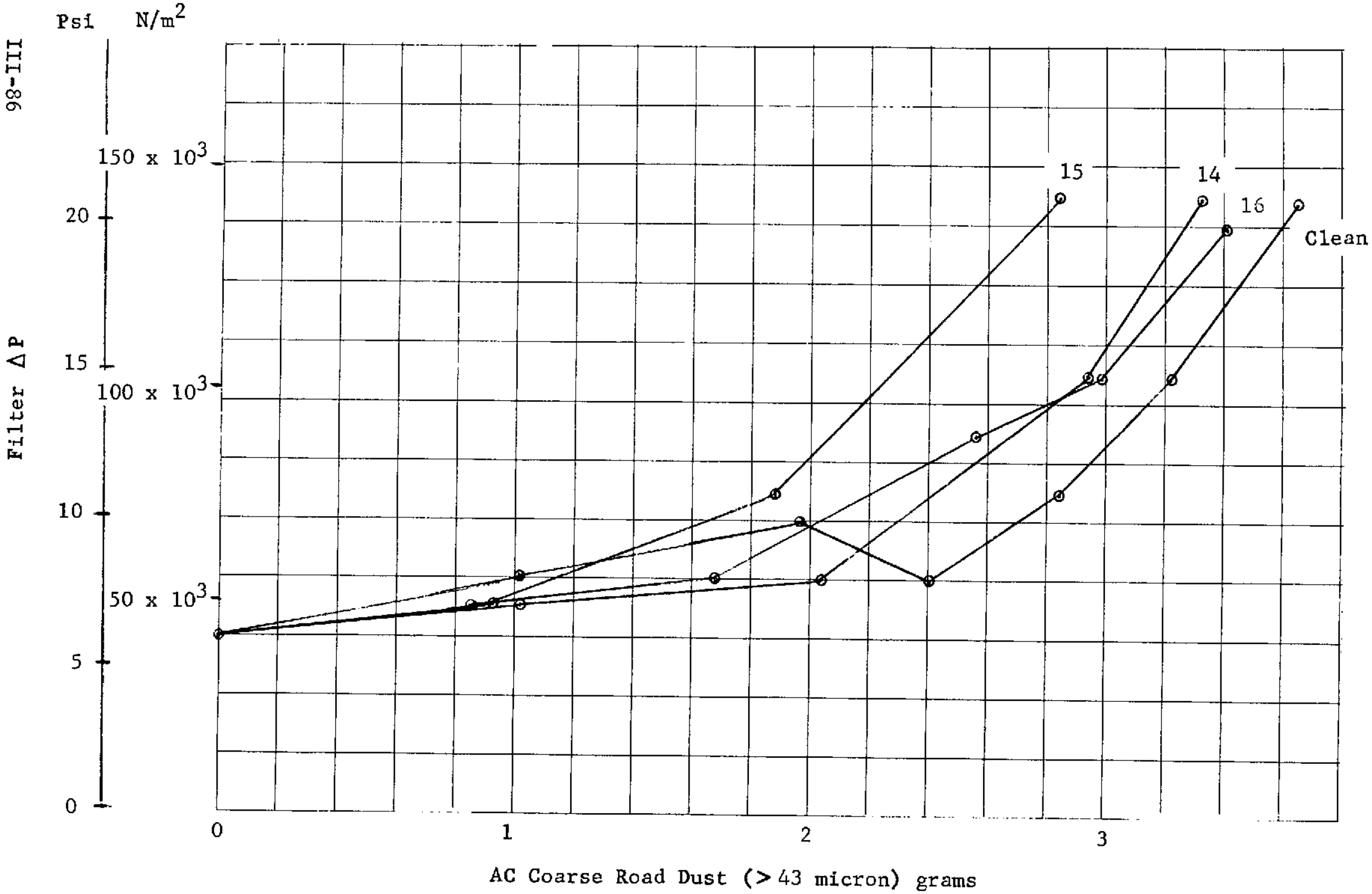


Figure III-42 Dirt Capacity - Backflush Performance Runs 14 thru 16

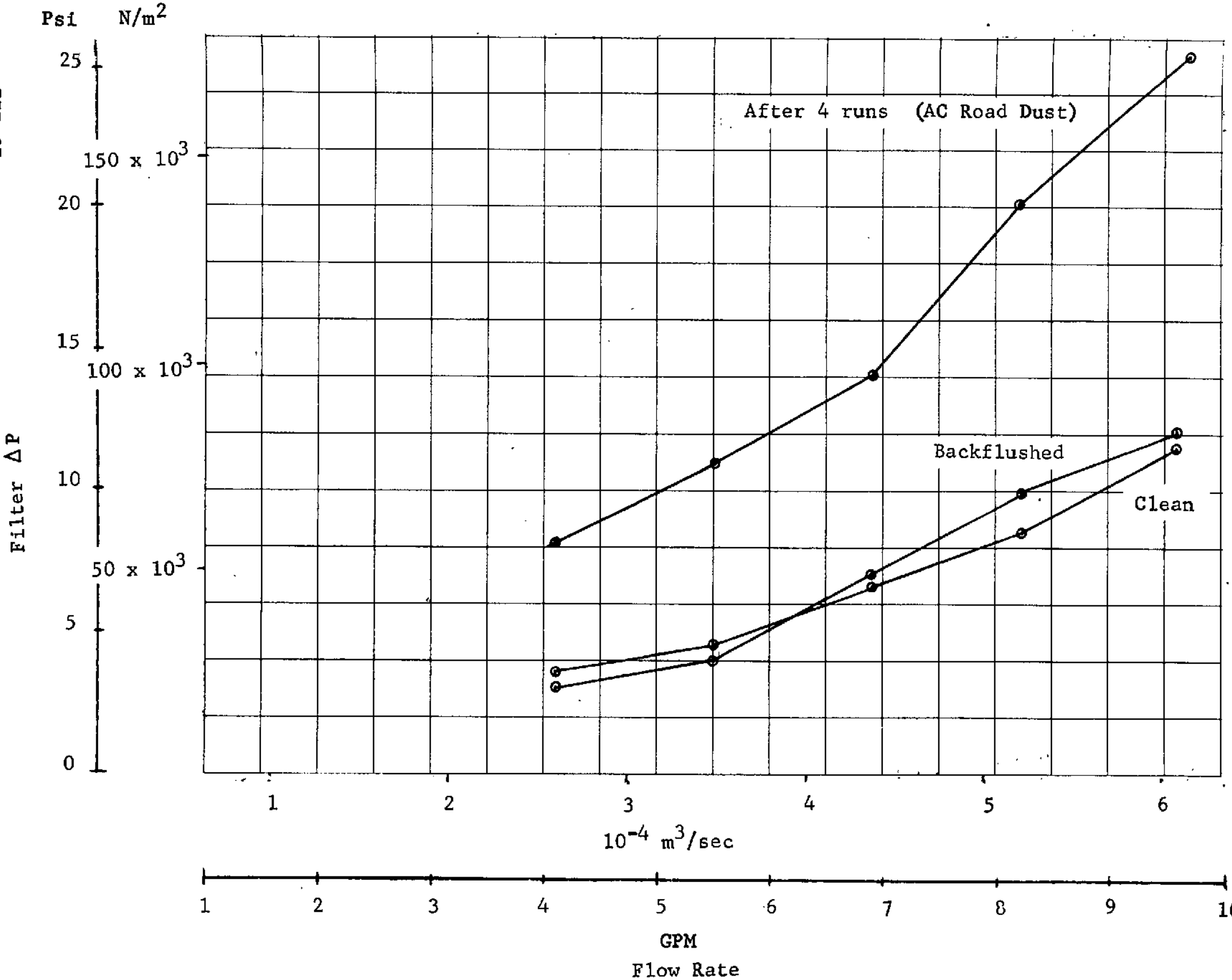


Figure III-43 Flow vs Pressure Drop - Secondary Filter is exaggerated at the higher flow rates. The changes at higher flow rates are more easily detected, and are a better indication of contaminant loading.

The data on the secondary filter shows that it was being loaded during the operation of the regeneration unit. The four runs had noticeably increased the pressure drop and possibly two additional runs would have increased the loading to the pressure cut-off point. Since the particle separator upstream of the filter is effective in removing larger particles, but has a lower efficiency for smaller particles, it would appear that the loading on the secondary filter is the result of smaller particles. If this is true, the secondary filter loading rate could be reduced by using a smaller vortex particle separator with better efficiency at the smaller size particles, but with an increased pressure drop.

Three filter regeneration unit performance tests were conducted using contaminants from a clothes washing machine and a whole body shower. The contaminants were obtained by the method described in the Test Contaminants section of this report, Section III.F.1. After being loaded, the filter was installed in the filter regeneration unit and backflushed for five minutes using the same procedure as described in the preceeding discussion. A summary of the results of these tests is shown in Table III-16.

The loading of the filter element with washing machine effluent, tests 18 and 19, occurred almost instantly and that with shower effluent occurred within two minutes at 4.29×10^{-4} m^3/sec (6.8 GPM). This implies several things; (1) that a mismatch of the filter element to the contaminant exists; and (2) that some property of the wash water contaminant accelerates the loading process. Two possibilities are currently theorized as the accelerating component of the wash water. The first of these is the detergent itself either forming a film on the surface of the filter causing the plugging or forming globules when the concentration of detergent is great enough, thus plugging the filter. The second possibility is that the wash water contains a large quantity of small particles, probably below 40 microns, which rapidly fill the pores in the filter plugging it while not significantly contributing any weight. These small particles may be contaminants from the dirty clothes or constituents of the detergent itself.

When regenerating the filter loaded with shower effluent, the net contaminant recovered was only .0032 grams, as compared to 0.05 grams for wash water. This may be caused by a significant difference in the constituents of the contaminants. It is not expected

Table III-16 Filter Regeneration Unit Performance Tests - Tests 18 thru 20

Test Number	CONTAMINANT RECOVERED (grams)				System Flow Rate x 10^{-4} m^3/sec (GPM)
	Separator Trap	Filter Bowl	Recovered on Millipore	Net Contaminant Recovered	
18 (Wash Water)	.0651	.0083	N/A	.0734	6.70 - 7.00 (10.6 - 11.1)
19 (Wash Water)	.0390	.0139	N/A	.0529	6.63 - 6.89 (10.5 - 10.9)
20 (Shower)	.0032	0	N/A	.0032	6.05 - 6.63 (9.6 - 10.5)
Regeneration of Secondary Filter (Wash & Shower Water)	.0117 (1)	.0009	N/A	.0126 (1)	6.31 - 6.44 (10.0 - 10.2)
Regeneration of 2nd Secondary Filter (Wash & Shower Water)	N/A	.0017	.0293 (2)	.0310	N/A

(1) Contaminant lost during test, estimated to be less than .1 gram

(2) Correction of .1045 grams because of use of 0.45 micron pad

that the contaminants from a shower would be as large as from a clothes washer. Thus, the particles backflushed would be smaller and more likely to not be removed by the separator. A difference in the type of loading is evident in the fact that the filter did not return to the same pressure drop versus flow rate curve following regeneration as did the other filters. The difference in filter pressure drop characteristics is shown in Figure III-44.

Between runs the pressure drop versus flow rate characteristics of the secondary filter were determined. The results of these checks are shown in Figure III-45. Following the three runs, the filter was regenerated and the pressure drop-flow characteristics returned to the clean characteristics. The amount of contaminant collected during regeneration, and the amount later backflushed into a millipore from the secondary filter (used in the regeneration), are shown in Table III-16. This data shows that the secondary filter may be cleaned by the filter regeneration unit.

Summary - The results of the performance tests show that the filter regeneration unit and its components are capable of effectively regenerating filter elements. The unit has indicated efficiencies of 92 to 95.5 percent in recovering the contaminants from a backflushed element.

The results show that a filter element can be regenerated and returned to the same pressure drop versus flow rate characteristics. The results of nine of these runs are shown on Figure III-46. These results indicate that the filter elements are being regenerated to their initial condition.

The tests also indicated that a problem may exist when using small micron filters in the process water system. It appears that the use of detergent, at least that used for the performance testing, has an extremely detrimental effect on filter capacity. The selection of a different detergent or the different matching of detergent and filter may minimize this problem.

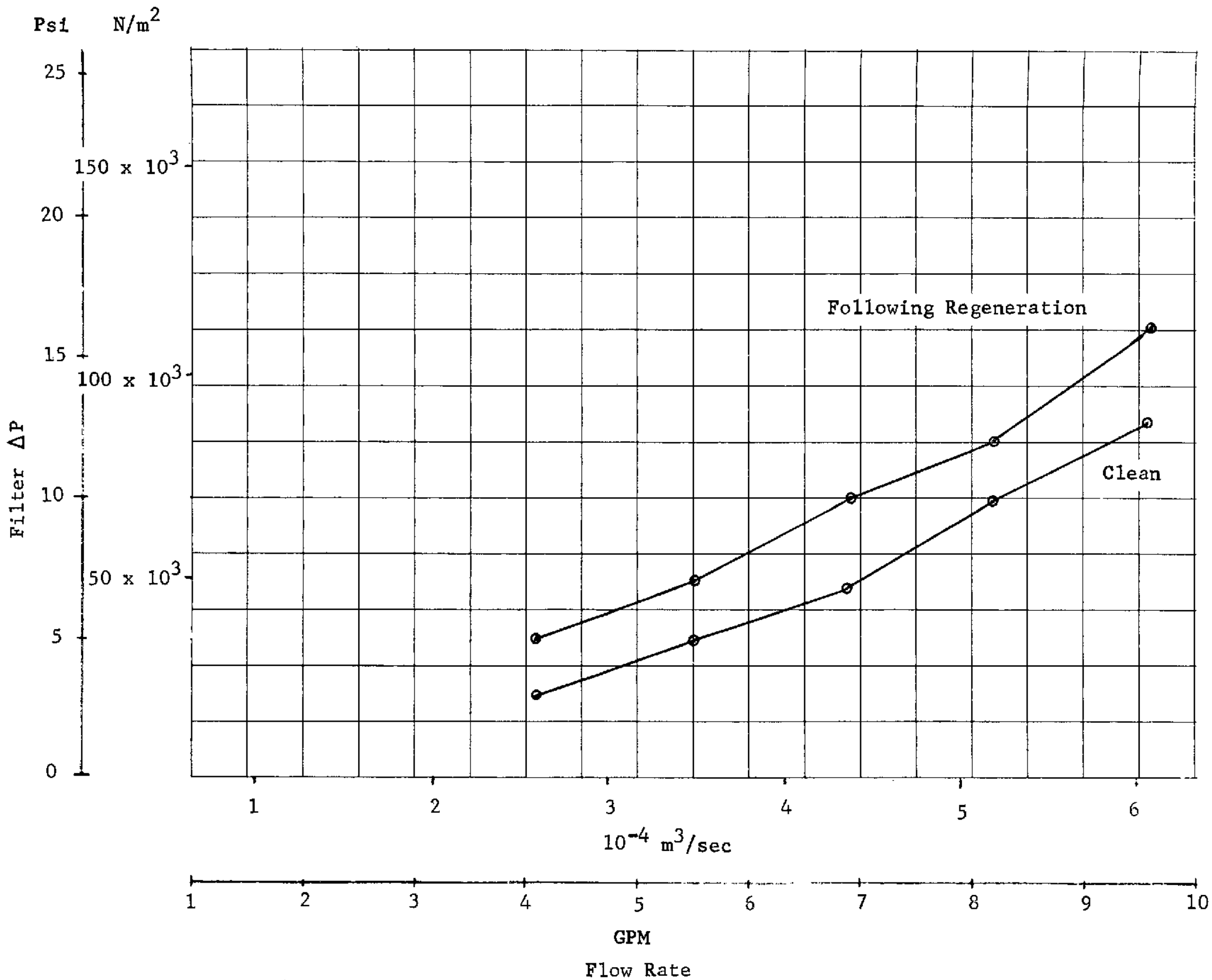


Figure III-44 Flow vs Pressure Drop - Shower Contaminated Filter

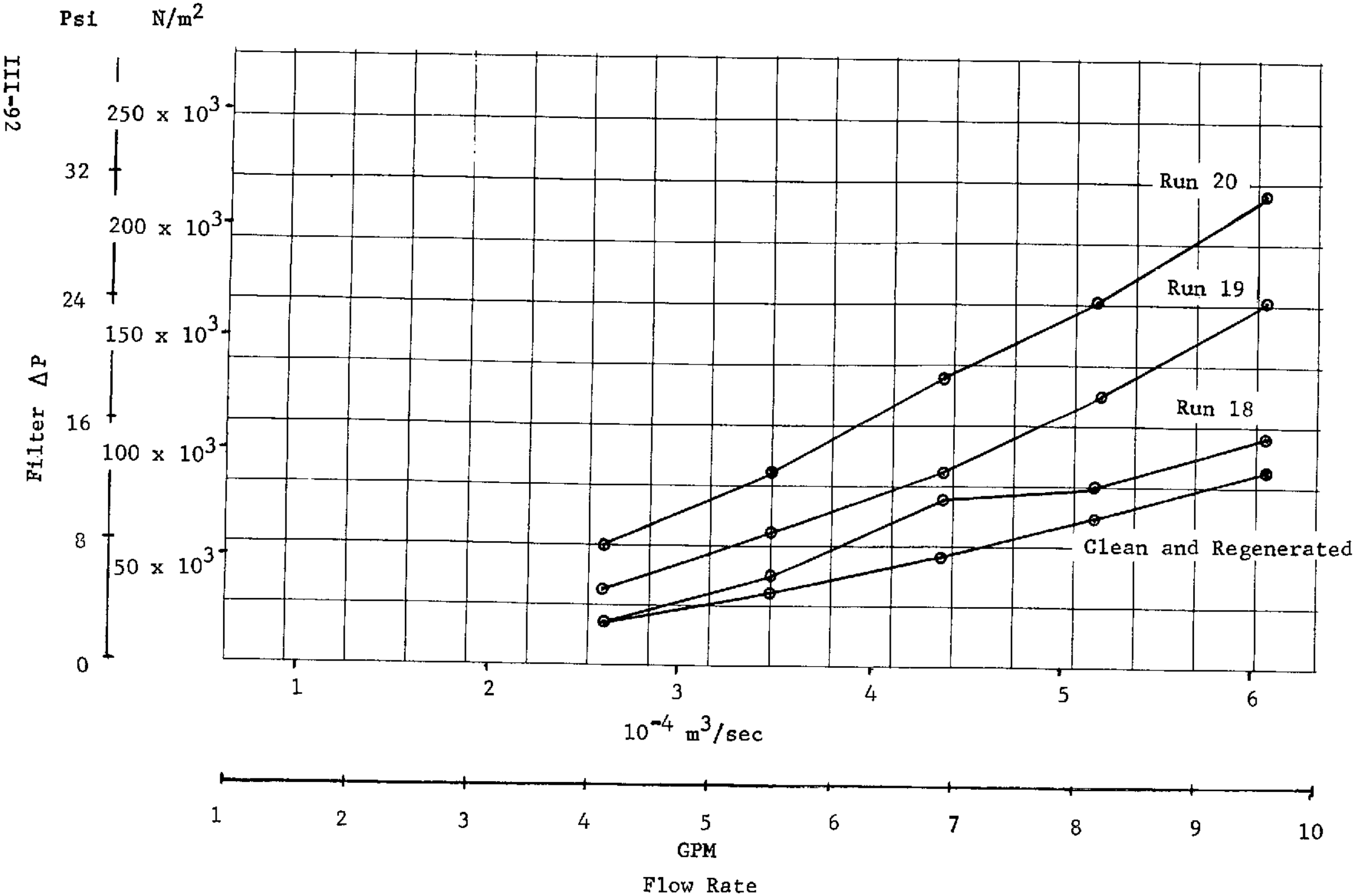


Figure III-45 Flow vs Pressure Drop - Secondary Filter

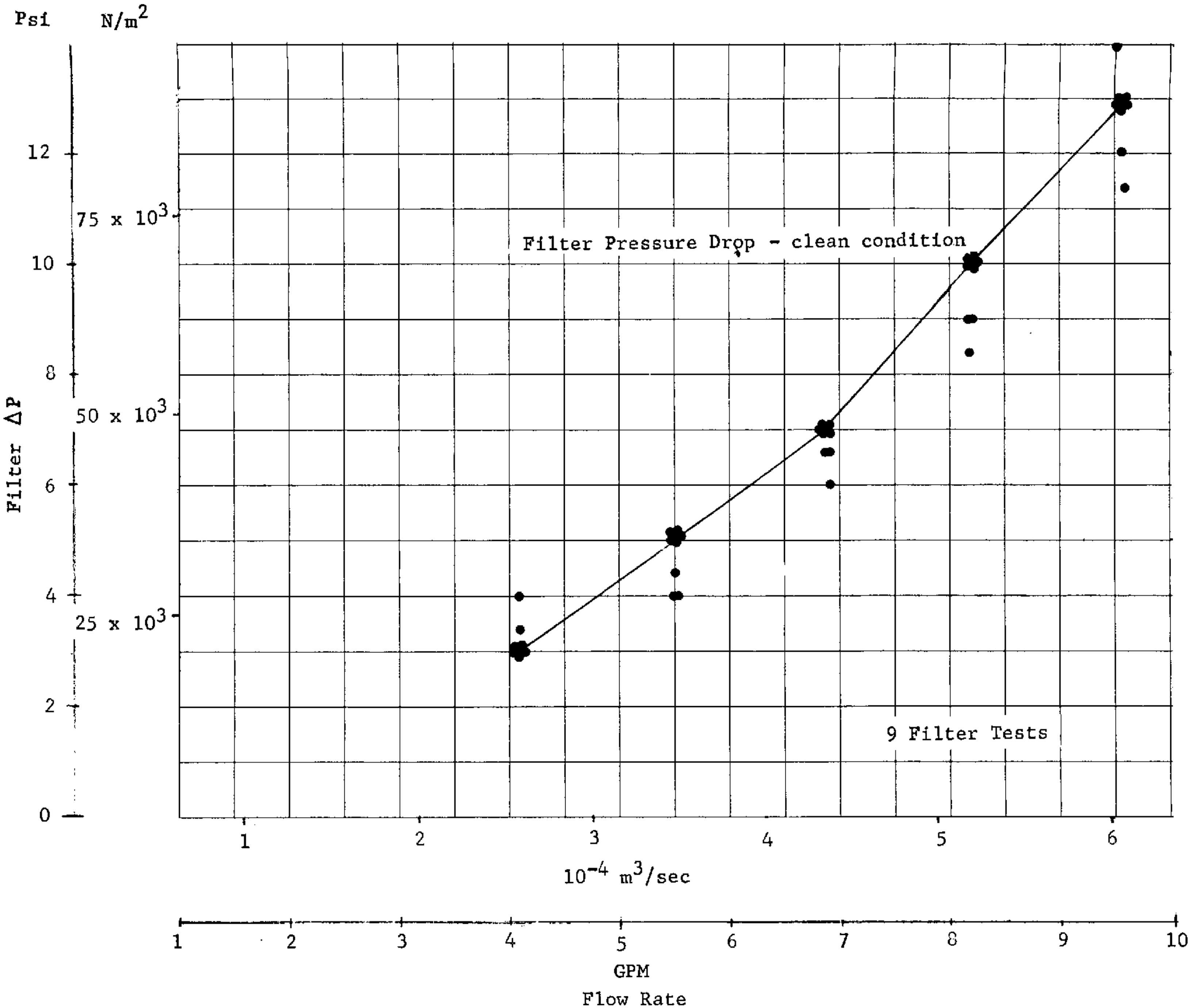


Figure III-46 Comparison of Clean vs Regenerated Filters

6. Zero-G Particle Trap Tests - A zero-g test of vortex separator particle traps was conducted on March 2, 1972 on the KC-135 aircraft. The test was conducted to determine if the particle trap concepts are effective in zero-g conditions.

The experiment (Figure III-47) was handheld with no additional interfaces. The vortex motion of the fluid (water) and particles (Basalt) was induced by hand, and visual and photographic data was used to evaluate the trap performance in zero-g.

Basalt was chosen as the test contaminant rather than AC road dust since basalt has better color contrast for photographic coverage. The Basalt particles are slightly larger and black in color. An attempt to use AC road dust in one-g produced only a clouding effect and no discernible particle movement. The use of Basalt allowed the motion of particles to be observed better.

The experiment contained two trap concepts with adjoining chambers. The particles were spun up in the trap chamber, and any migration of particles to the inner chamber would have indicated that the particles were migrating out of the trap.

One trap, design number 1, has a slot milled on a tangent to the inside diameter of the vortex chamber. The particles exit through the slot and the concept is that they will have a difficult path to re-enter the slot. No flow forces should exist in true zero-g after the vortex motion has stopped.

The second trap, design number 2, has a vane mounted on the tangential slot. The concept is that the particles will travel down the spiral ramp and "pack" at the bottom with a very difficult path back to the slot.

A total of eleven tests (20 parabolas) were performed on both ends of the experiments. Tests were conducted with the experiment free floating and with the experiment restrained by the free floating test subject. Each test was performed for the duration of the zero-g portion of the parabola, or approximately 30 seconds.

The experiment was spun up while in zero-g, by moving the experiment in a circular motion using the arrow on the clamp as a guide to insure proper rotation. This motion creates circulation in the trap similar to that obtained during separator operation.

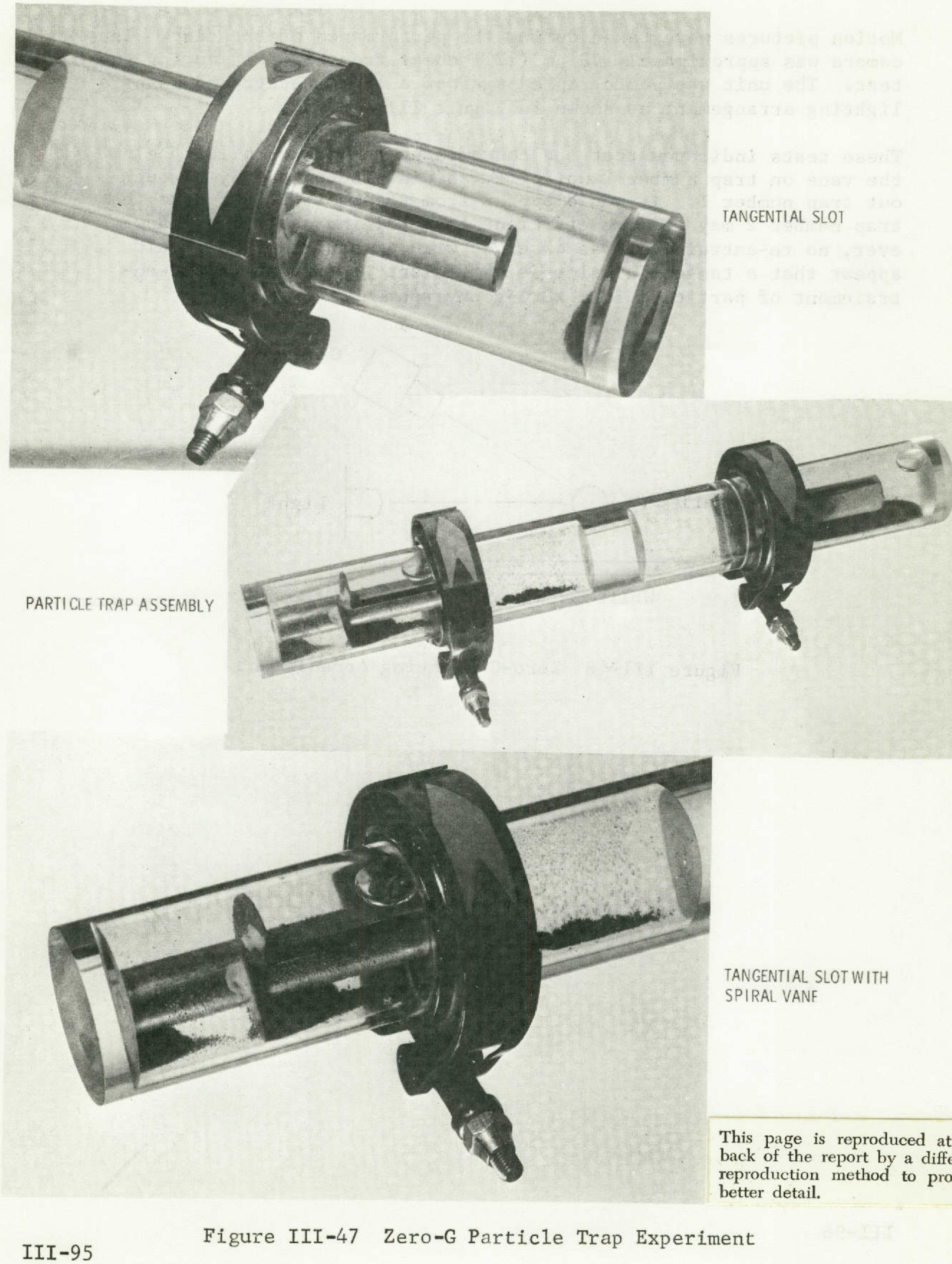


Figure III-47 Zero-G Particle Trap Experiment

Motion pictures were taken during the performance of the test. The camera was approximately 40 cm (12 inches) from the unit during the test. The unit was photographed against a light background using a lighting arrangement as shown in Figure III-48.

These tests indicated that the contaminant tended to collect below the vane on trap number 2 while it was distributed evenly throughout trap number 1. It would appear from the photographic data that trap number 2 may be more efficient in retaining particles. However, no re-entrainment was observed with either trap. It would appear that a tangential slot is sufficient to prevent the re-entrainment of particles in a zero-g environment.

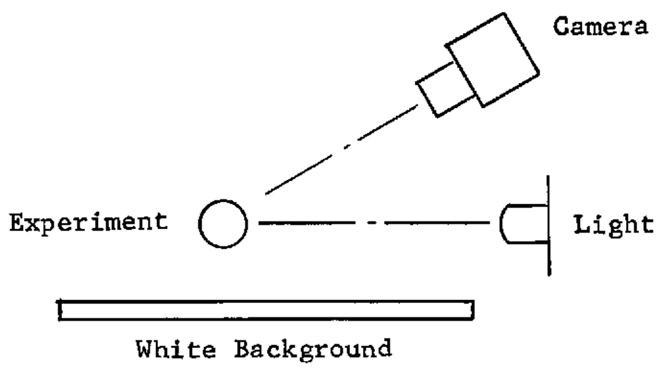


Figure III-48 Zero-G Lighting Arrangement

A maintainable filter that offers an alternative to filter regeneration was delivered on this contract. The maintainable filter is designed so that the filter canister and element can be quickly changed out with no leakage or spillage of fluid. The filter element can be connected or disconnected simply by a hand torque operation that does not require any tools. This type of design precludes draining a fluid system, purging, and fill and drain operations.

The maintainable filter provides a solution to systems requiring quick turn-around (Shuttle), for fluids that involve safety in handling (propellants and bacteria-laden systems), for clean fluid systems whereby the introduction of bacteria cannot be tolerated (potable water), and for one-of-a-kind fluids where it may not be practical to supply an additional filter regeneration unit.

A. DESCRIPTION AND OPERATION

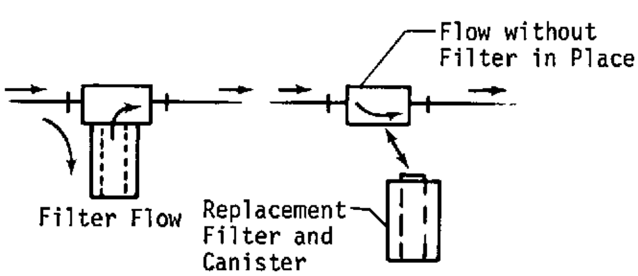


Figure IV-1 Maintainable Filter Replacement Technique

The maintainable filter provides a quick change of the filter canister and element with no leakage or spillage of fluid. The fluid system does not have to be shut down for the replacement operation since the system flow automatically bypasses the filter circuit when the filter canister is removed (Fig. IV-1). Since both connections automatically seal at disconnect, the maintainable filter is applicable to the zero-g as well as the one-g environment. The concepts involved in the disconnect mechanism are fundamental in self-sealing disconnects where the inlet and return channels of flow are self-sealing. The filter can be connected or disconnected simply by a hand torque operation that does not require any tools. The disconnect has two concentric spring-loaded poppets (Fig. IV-2 and IV-3) that engage the filter

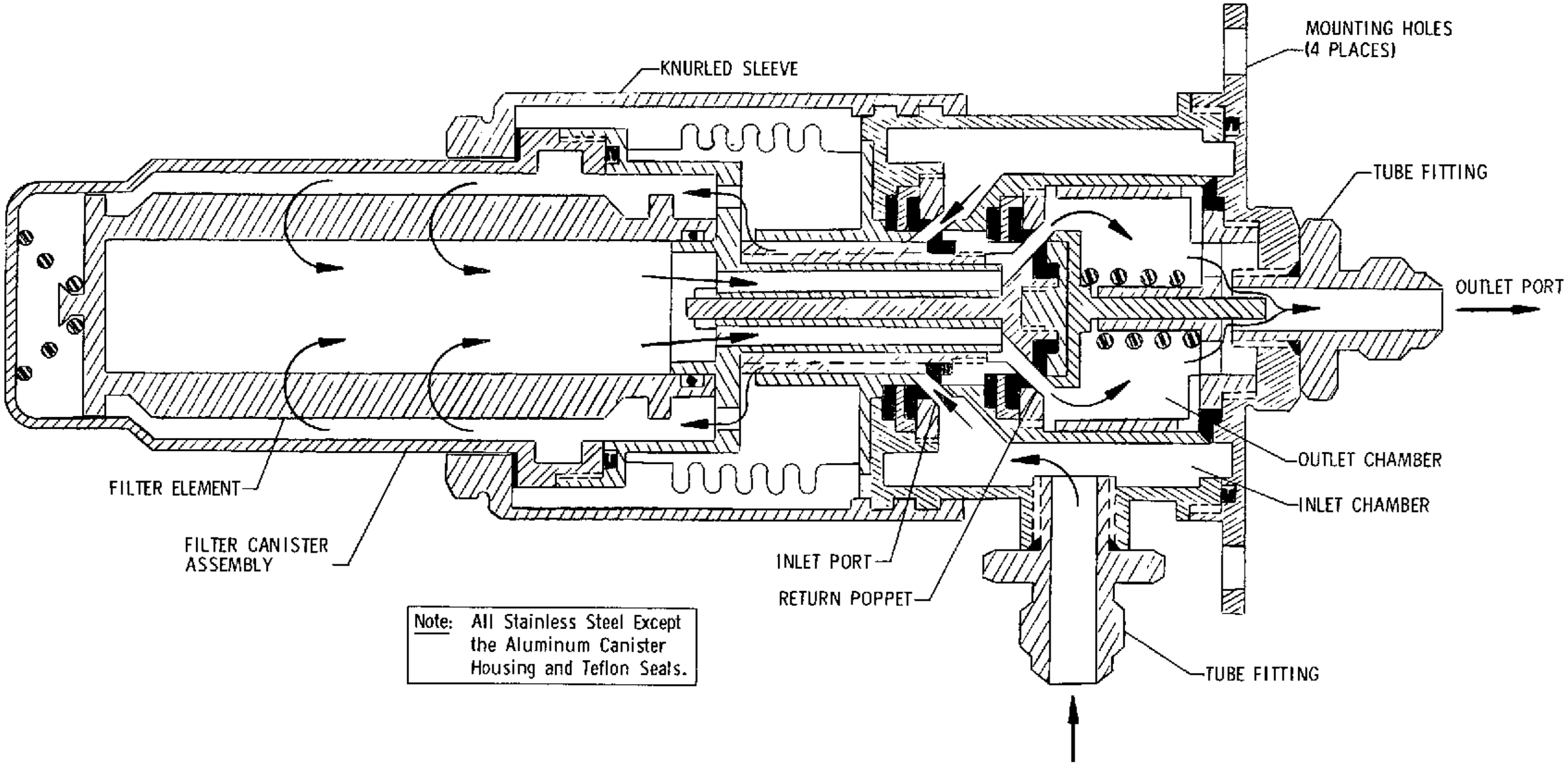


Figure IV-2 Maintainable Filter - Connected

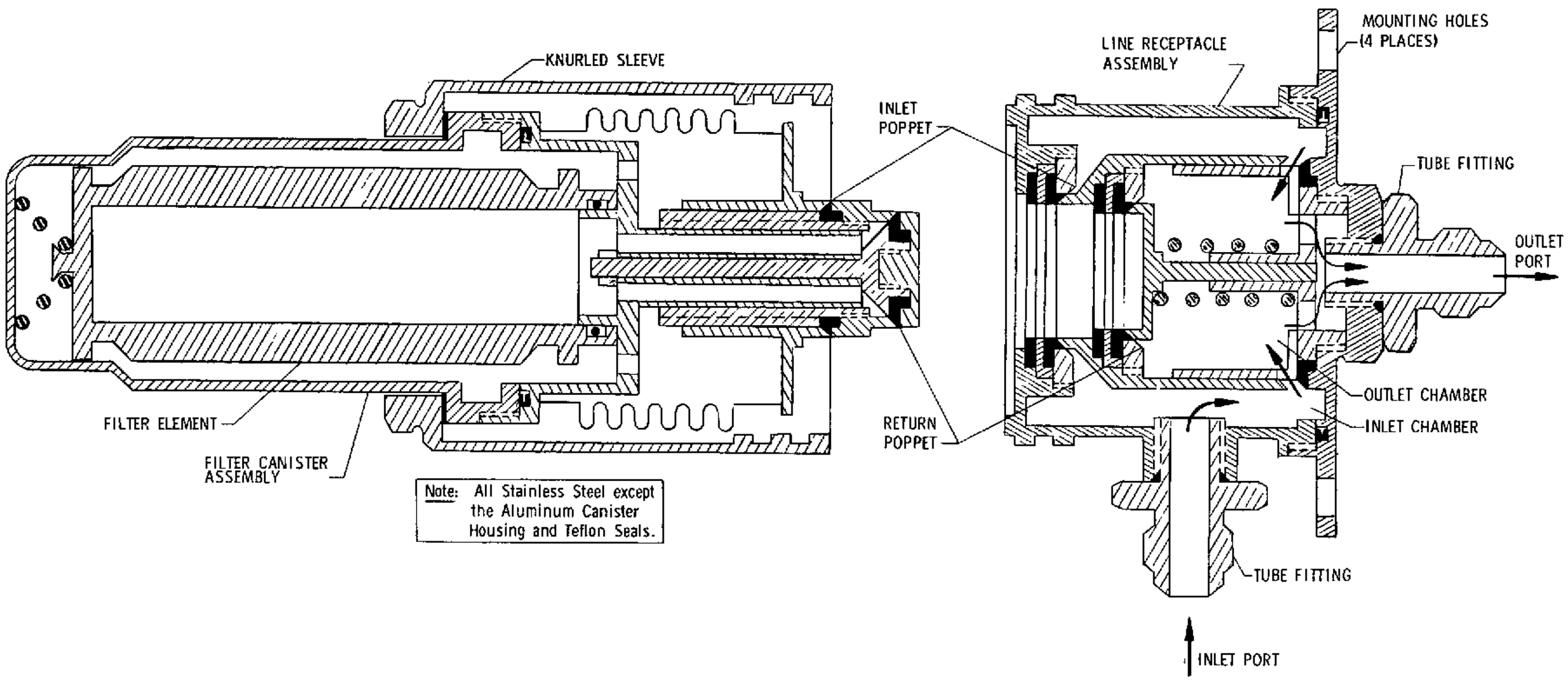


Figure IV-3 Maintainable Filter - Disconnected canister so the return and inlet poppets are sequentially opened during connection or closed at disconnect. When connecting the filter canister, the knurled sleeve is screwed onto the line receptacle and provides the force to sequentially open the poppets. The inverse procedure applies for disconnect. In both operations only a moderate one-handed effort is required.

While connected, the system fluid passes through the inlet port and into the inlet chamber where it continues past the inlet poppet into the filter canister. The fluid then passes through the filter element and back through the outlet poppets. From here the fluid passes through the outlet chamber and out the outlet port (Fig. IV-2).

With the canister disconnected, the fluid passes through the inlet port and into the inlet chamber where it goes directly into the outlet chamber and exits through the outlet port (Fig. IV-3).

The filter element contained within the canister can be easily removed with common hand tools (two wrenches). If the filters were used on the Space Shuttle where ground maintenance is applicable, the filter elements could be removed from the canister and either refurbished with a new element or cleaned. For filters that would be replaced in the Space Station, the contaminated filter canisters could be refurbished aboard the Space Station, or transferred back to earth via the Shuttle and cleaned as previously described. An alternative would be to have a regenerative filter system for these maintainable filters in the Space Station.

The prototype maintainable filter built by Martin Marietta (Fig. IV-4 and IV-5) was originally designed for an attitude control propellant system to facilitate maintenance of a highly toxic propellant system. The materials for this design are stainless steel, aluminum, polyurathane, and Teflon, which are compatible with most fluids. For water-based systems, the aluminum filter canister should be changed to stainless steel since aluminum corrodes badly during prolonged use in a water system. The filter design can be adapted to any sized element, depending on the requirements of the system. The design has many applications for both the Space Shuttle and Space Station fluid systems.

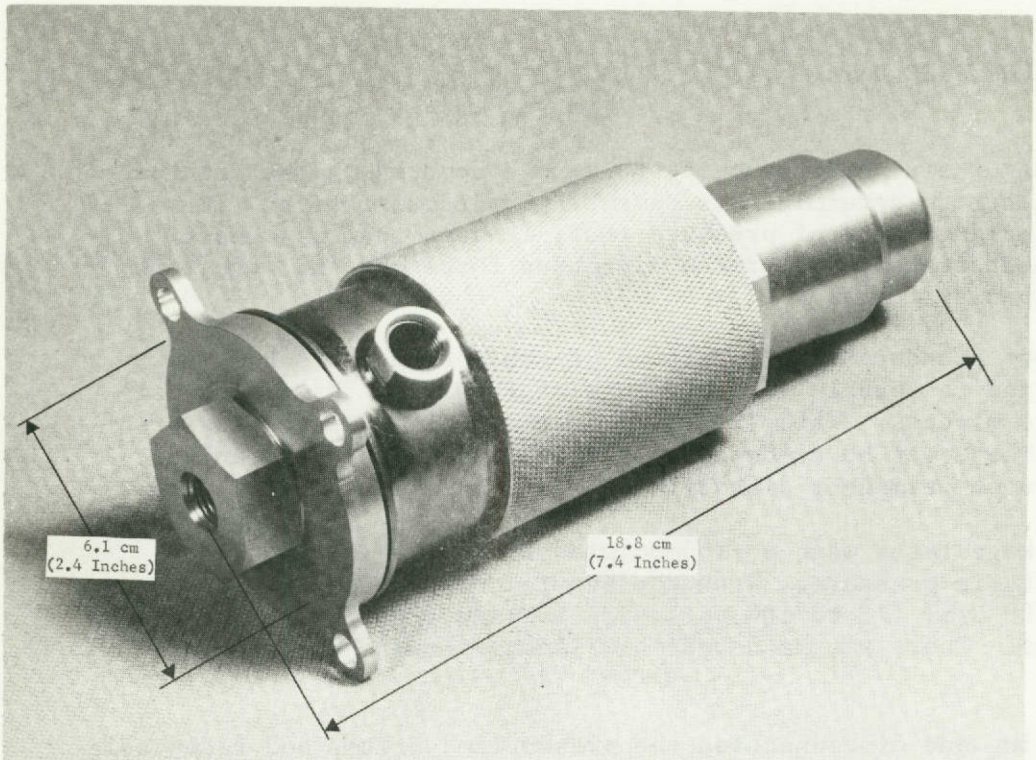


Figure IV-4 Maintainable Filter-Connected

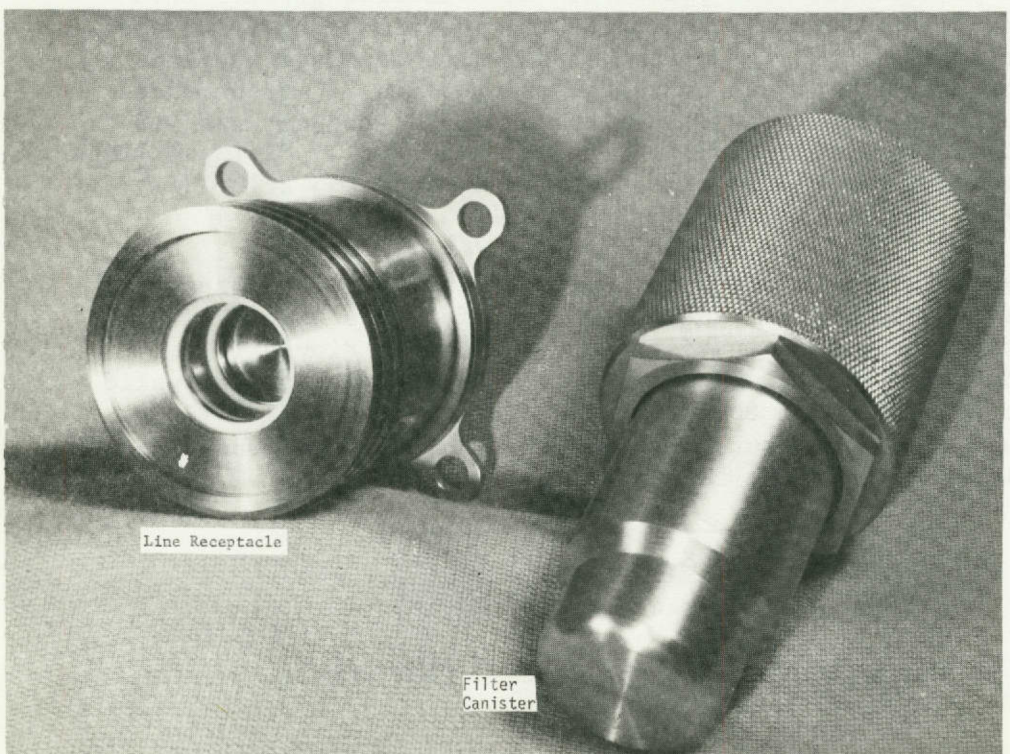


Figure IV-5 Maintainable Filter-Disconnected

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B. PERFORMANCE DATA

A series of six performance tests were conducted on the maintainable filter to determine its operating characteristics. These tests included a proof pressure test, leakage tests, connect/disconnect tests to determine operating force and spillage, and flow capacity tests.

The proof pressure test consisted of subjecting the assembled filter and receptacle to a pressure of 1030 x 10^3 N/m^2 (150 psi) for five minutes. Water was used as the pressurant for the proof test. There was no evidence of leakage during the test and no evidence of permanent distortion.

The leakage tests were performed with the maintainable filter under static pressure. With the static pressure between 520 and 690 x 10^3 N/m^2 (75 to 100 psi), the leakage from the receptacle was zero. There was no detectable leakage from the assembled unit.

Connecting and disconnecting the pressurized filter and receptacle was accomplished without difficulty at pressures below 895 x 10^3 N/m^2 (130 psi). The torque required to connect and disconnect increased perceptibly with pressure. At pressures greater than 1035 x 10^3 N/m^2 (150 psi) the torque required for connection and disconnection was high. A change to a larger diameter knurled sleeve, or use of a wrench on the flats provided, is recommended for higher pressures. Fluid spillage during disconnect was 0.3 cc at a test pressure of 1035 x 10^3 N/m^2 (150 psi). Fluid spillage during connection was zero at a test pressure of 895 x 10^3 N/m^2 (130 psi).

The flow-pressure drop characteristics of the filter are shown in Figure IV-6 for water, and Figure IV-7 for gaseous nitrogen. A schematic of the test installation is shown in Figure IV-8. The gaseous nitrogen flow pressure drop characteristics are valid for inlet conditions of 600 x 10^3 N/m^2 (87 psia) and 21°C (70°F) only; however, the pressure drop at other inlet conditions can be calculated through the relationship:

$$\Delta P = P_c \times \sqrt{\frac{0.69\ (kg/m^3)}{\text{desired density}\ (kg/m^3)}}$$

where P_c is the curve value at the desired flow rate.

The flow path of the receptacle is different when the filter is not connected than it is when connected. Thus, the curves do not indicate what percentage of pressure drop may be attributed to the receptacle when connected. It is likely that the 1/4-inch AN union fitting in the receptacle accounts for a significant portion of the pressure drop.

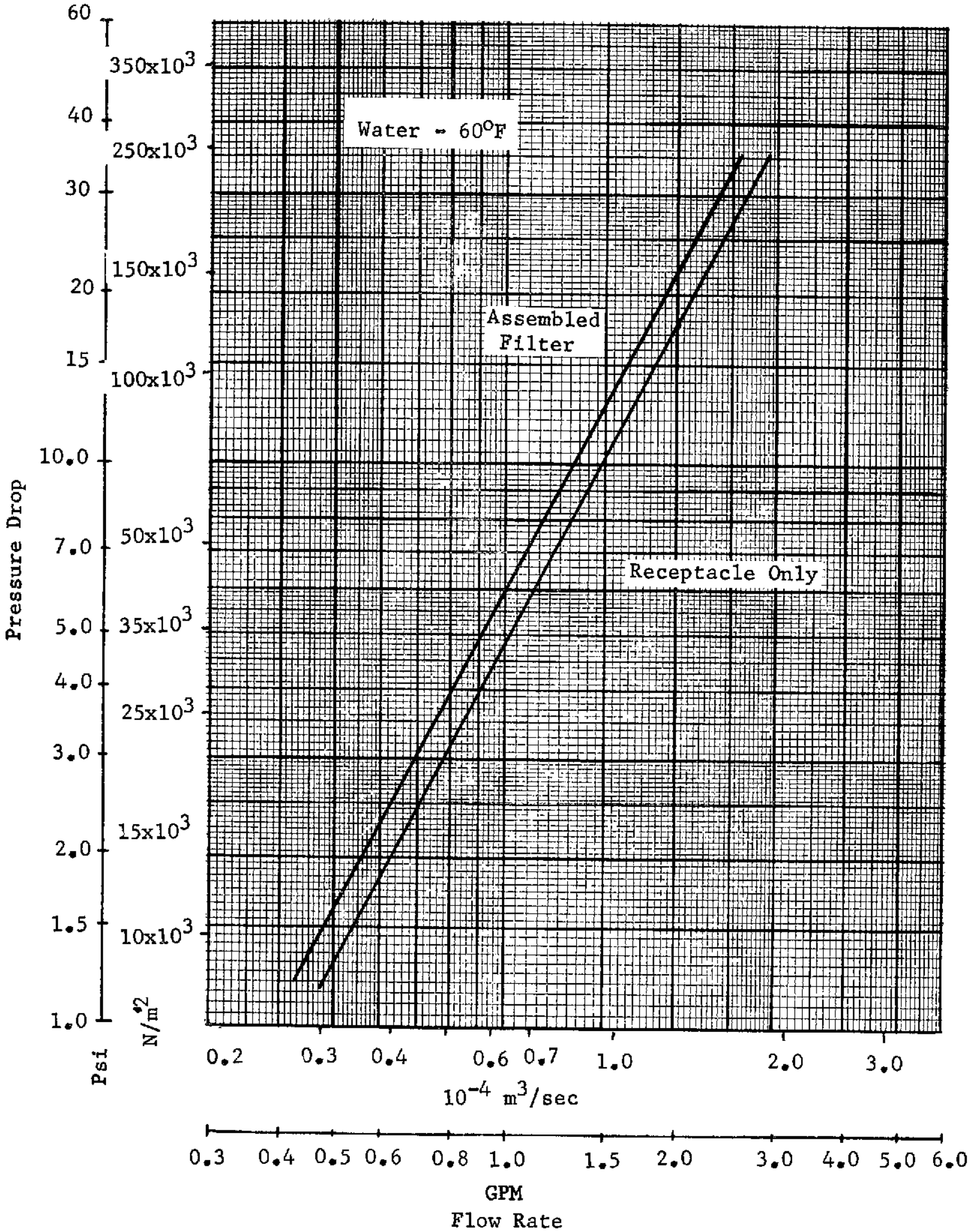

Figure IV-6 Maintainable Filter - Pressure Drop (water)

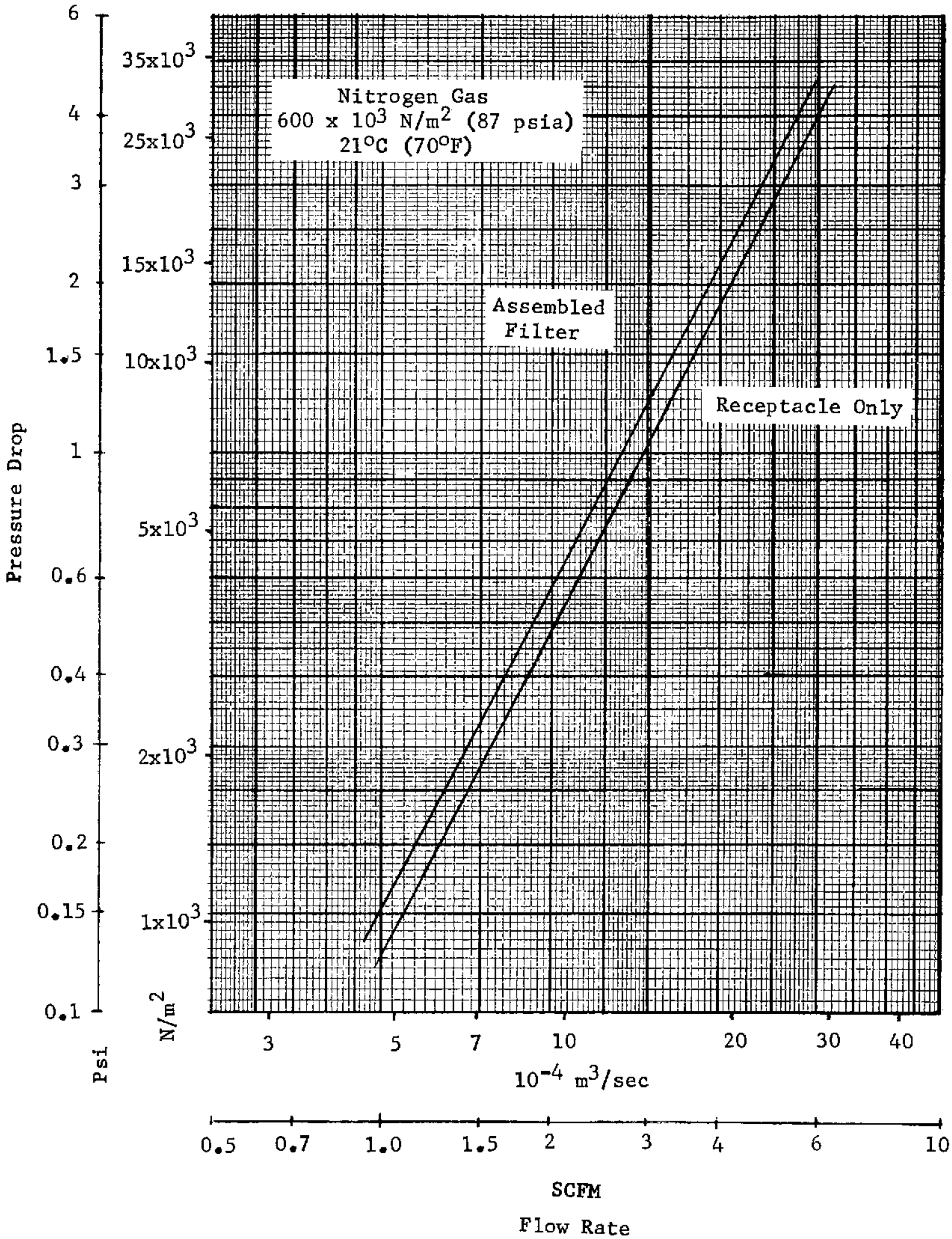

Figure IV-7 Maintainable Filter - Pressure Drop (nitrogen)

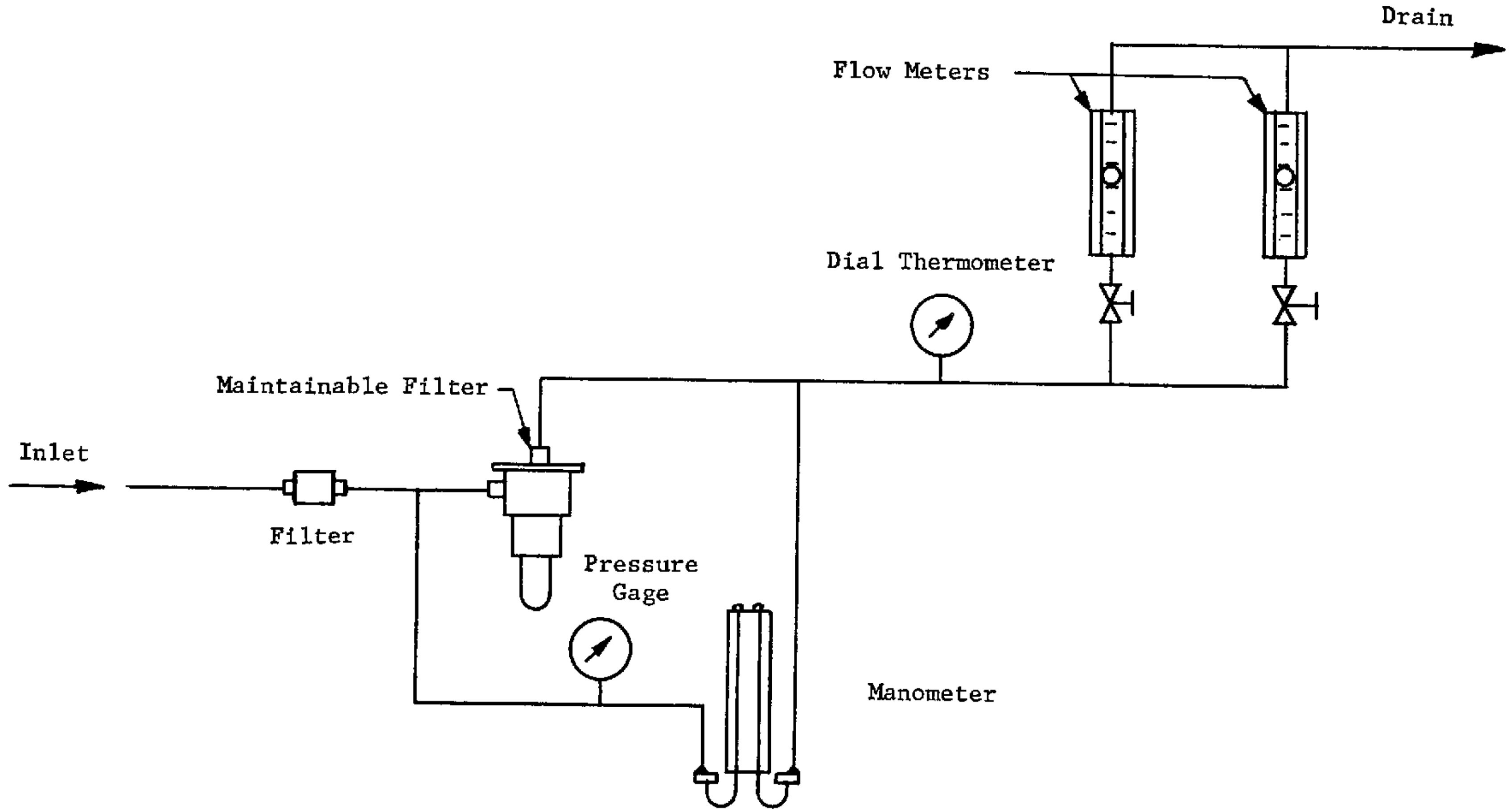

Figure IV-8 Maintainable Filter - Test Schematic

V. INTERFACE REQUIREMENTS

The following interface requirements are based upon the selected filter regeneration concept derived in this development program, namely that of a portable unit. Using this technique, the regeneration unit is brought to the respective fluid system interface (Figure V-1), or the regenerative filter can be disconnected from the system and brought to the regeneration unit (Figure V-2). In either case the fluid system filter must be of a special regenerative configuration having a special backflush filter element and an impingement jet.

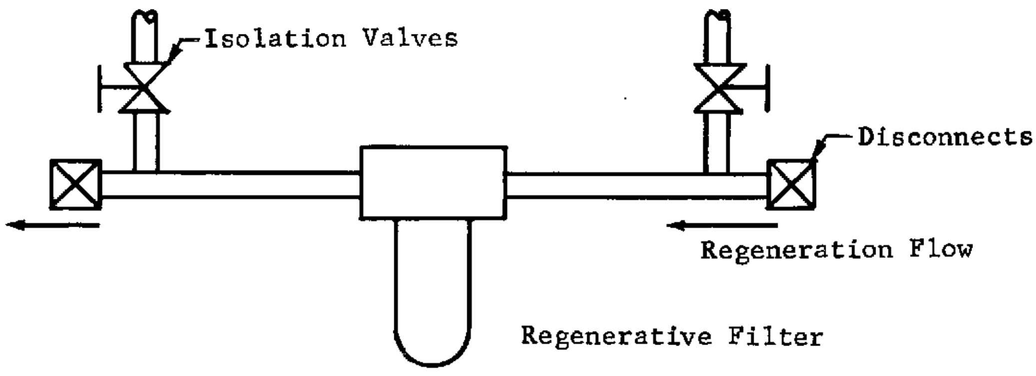

Figure V-1 Inplace Regenerative Filter

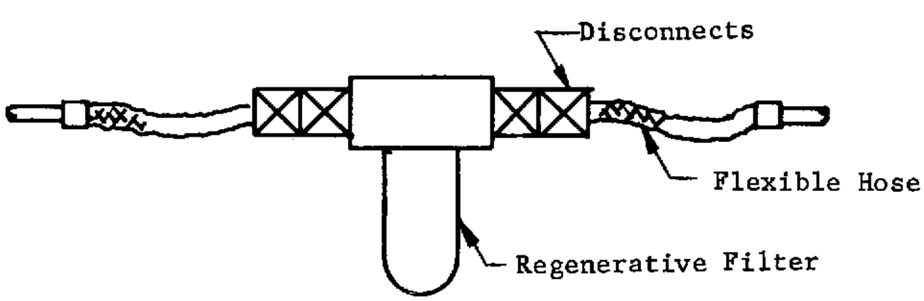

Figure V-2 Removable Regenerative Filter

The basic interface requirements specified are for the development unit, but where possible, an approximation is presented for what a flight configuration would represent. The interface requirements are based specifically on the portable regeneration unit concept where the unit is transferred to the fluid system interface (Figure V-1).

Each fluid system interface requires two fluid self-sealing connectors; an inlet and outlet nipple half of a quick disconnect which are color coded or keyed to mate with the connectors on the filter regeneration unit. If the disconnects are panel mounted, the nipple halves should be recessed to eliminate protrusions, and should have sufficient hand clearance to make the connection. With the development unit the nipple halves can be located, relative to each other, as close as 15.2 cm (6 inches) or as far as 45.7 cm (18 inches).

The fluid system plumbing between the disconnects (Figure V-1) must be specified to allow proper operation of the regeneration unit. The plumbing should be stainless steel with isolation valves located as shown to prevent circulation of the fluid system during the regeneration process. These isolation valves also provide maintainability of the regenerative filter in the event of a total failure. The valves can be simple ball valves which add little to the pressure drop of the fluid system. The tubing and fittings between the quick disconnects should provide a pressure drop no greater than 34.5×10^3 N/m^2 (5 psid), not including the regenerative filter, at a flow rate of 6.3×10^{-4} m^3/sec (10 GPM). All plumbing between the regenerative filter and the outlet disconnect should have no obstructions or dead flow areas where contaminants could lodge. This necessitates that the fluid system flow branch be perpendicular to the regeneration flow path as shown in Figure V-1. The regeneration flow rate will be as high as 6.95×10^{-4} m^3/sec (11 GPM) at a pulsating working pressure of 1378×10^3 N/m^2 (200 psig), therefore all of the related fluid system plumbing and components between the interfaces must meet these requirements. The working pressure of the flight regeneration unit would be reduced to 689×10^3 N/m^2 (100 psig) but the flow rate will remain the same.

A special regenerative filter must be used in the fluid system to provide the filter regeneration capability. The regenerative filter includes a stainless steel backflushable element and an impingement jet. The one designed for the development regeneration unit (see Figure III-2) is rated at 10 microns nominal-25 microns absolute for a normal system flow rate of 4.29×10^{-4} m^3/sec (6.8 GPM) and pressures up to 1378×10^3 N/m^2 (200 psig). For the flight fluid systems, the filter element rating can be varied in accordance with the specific system filtration requirements but must withstand the backflush flow rates and working pressures specified above. For commonality, logistics, and maintenance reasons it is recommended that the same regenerative filter construction and size be used for all fluid systems but with different filter element micron ratings to meet the specific fluid system particulate requirements. For the flight system the regenerative filter can be decreased in size and weight from that of the development filter.

The condition of the regenerative filter must be monitored to determine when it requires cleaning. For the developed regenerative filter, two pressure taps are provided in the filter body to read differential pressure which will indicate when the filter element requires cleaning. A typical contaminant loading curve for the regenerative filter is shown in Figure V-3. By locating the data point on the curve, the relative condition of the regenerative filter is established. The maximum allowable pressure drop across

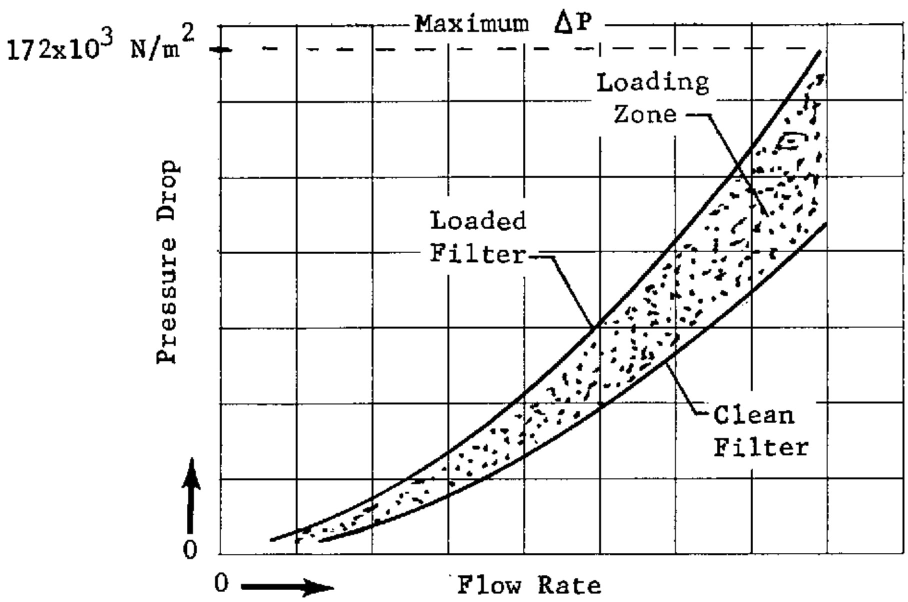

Figure V-3 Typical Regenerative Filter Loading Curve

the element is 138 x 10^3 to 172 x 10^3 N/m^2 (20 to 25 psid). To obtain the data point, the differential pressure across the filter is required as well as the flow rate through it. For flight systems the differential pressure is easily obtained by the use of pressure transducers, with the Onboard Checkout System (OCS) providing the monitoring function. Since most of the systems have relatively constant flow rates when operating, which can be established during installation or checkout, the need for flow meters can be eliminated. The differential pressure is therefore the only parameter that needs monitoring. The gage or monitoring equipment can be located at the fluid system interface and/or at the Onboard Checkout System (OCS).

An electrical power supply outlet is required for the regeneration unit. The development unit requires a standard 3-prong grounded receptacle with a 115 volt, 60 Hz, 1 phase supply capable of providing 3300 watts power for a period of five minutes. A more efficient flight unit should require a 200 volt, 400 Hz, 3 phase supply capable of providing 2000 watts for a period of five minutes. For the flight unit, the length of the power supply chord and location of the receptacle must be integrated so that the receptacle can be used for two or more fluid system interfaces.

The development unit has a volume of approximately .074 m^3 (2.6 ft^3) and weighs 45.5 kg (100 lb). The regeneration unit connection hoses are .76m (30 inches) long. A flight unit would have an approximate volume of .023 m^3 (.8 ft^3) and a weight of 11.3 kg (25 lb).

A mounting or restraint device is required for a flight regeneration unit in a zero-g environment. This can be as simple as a velcro tether.

Table V-1 summarizes the interface requirements for the overall filter regeneration system. Interfaces are shown for both the development unit and a flight unit. The interfaces for the flight unit are based on potential design considerations.

Table V-1 Summary of Fluid System Interface Requirements

Requirement	To Interface With: Development Unit	To Interface With: Flight Unit
1. Inlet/Outlet Fluid Disconnect	Nipple half - quick disconnect (Parker-Hannifin P/N SSH4-63). (2 required)	Zero leakage type quick disconnect for zero-g operation.
2. Electrical Receptacle & Supply	Standard 3-Prong Grounded receptacle rated at 25 amps with 30 amp capacity and 3300 watts for five minute period.	Zero-G receptacle (Bendix Corporation P/N 2G0E17-6PA) with 200 volt, 400 Hz, 3 phase supply and 2000 watts for five-minute period.
3. Mechanical Mount	Horizontal Surface for .074 m^3 (2.6 ft^3) unit weighing 45.4 kg (100 lb).	Clamps, tether, etc. for .023 m^3 (.8 ft^3) unit weighing 11.3 kg (25 lb).
4. Internal Plumbing	1) Two isolation valves 2) 34.5×10^3 N/m^2 (5 psi) max pressure drop between QD's at 6.3×10^{-4} m^3/sec (10 GPM) not including regenerative filter. 3) Regeneration pressure of 1378×10^3 N/m^2 (200 psi).	Same as Development Unit except regeneration pressure of 6.89×10^3 N/m^2 (100 psi).
5. Regenerative Filter	Martin Marietta P/N RES31704-009 includes: 1) Alum Filter Body. 2) Special AN6235-2A element rated at 10 micron nominal, 25 micron absolute. 3) Special impingement jet.	Same as Development Unit except lighter with material more compatible and element rated as required for applicable fluid system.
6. ΔP monitoring device across Regenerative Filter	1) ΔP gauge, or 2) ΔP transducer and readout device, or 3) Pressure drop limit indicator (pop-up device).	Same as Development Unit.

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